Musings on Jet Medium Interaction

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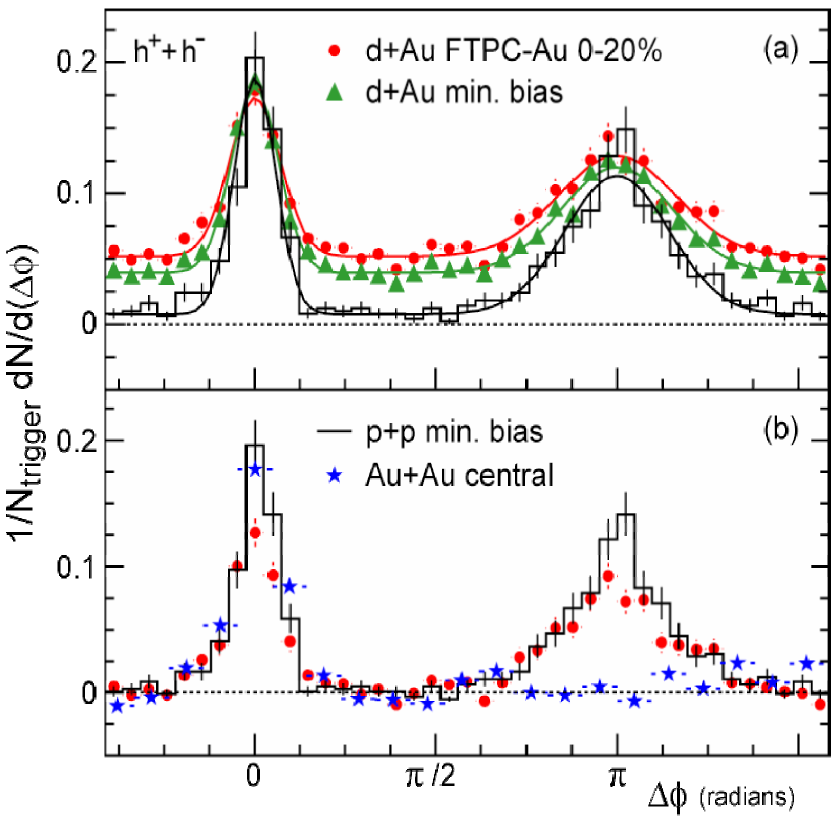
in the City of New York

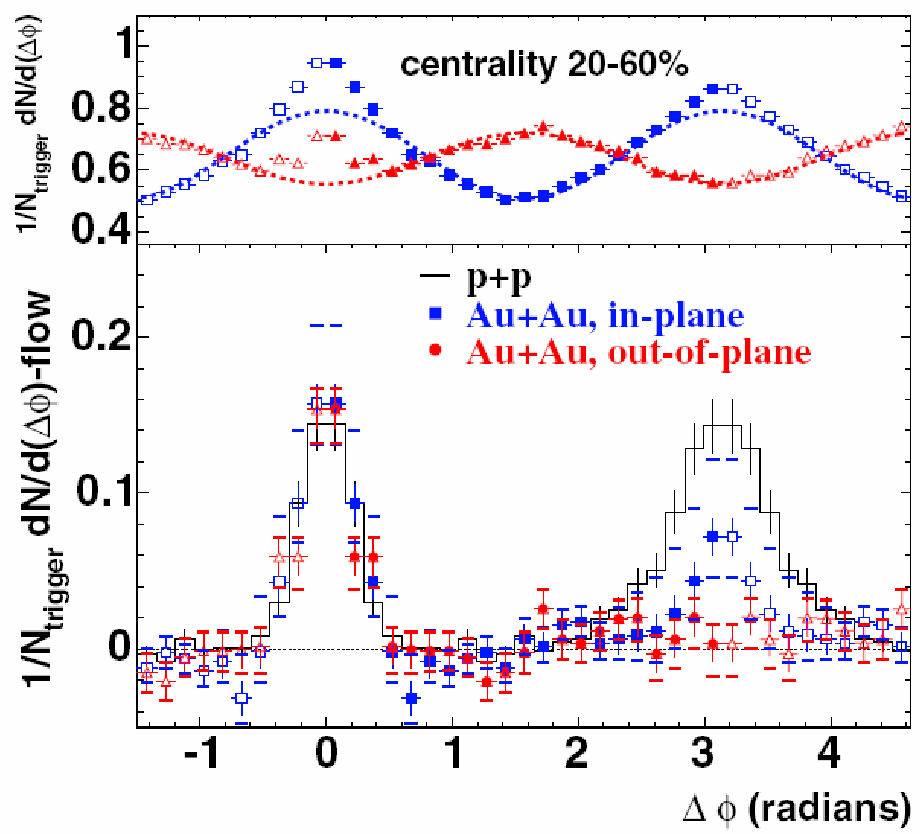
The Success of Jet-Quenching at RHIC

Away-side jet suppressed at moderately high pT

STAR - PRL91 (2003) 072304



Suppression varies with path length



Away side jet suppression consistent with jet-quenching picture

Jet Tomography and Medium Modification

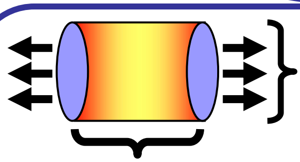
Jet “loses” energy and responds to the medium
-> possibility to use jet response for “tomographic imaging”

But the “lost” energy is not lost, it’s transferred to the medium and can excite the medium -> if medium is sufficiently strongly interacting, can we observe the medium’s “response” to the jet?
-> possibility to use medium response to the jet as a tool to study the novel QCD matter formed at RHIC

In this talk concentrate on the medium response of the jet

Strongly Interacting Matter at RHIC

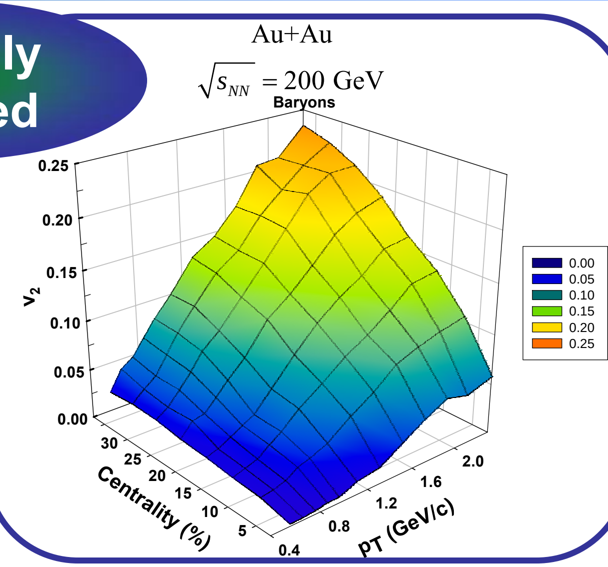
high energy densities



$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

$\varepsilon_{Bjorken} \sim 5 - 15\ GeV/fm^3$
$\sim 35 - 100\ \varepsilon_0$

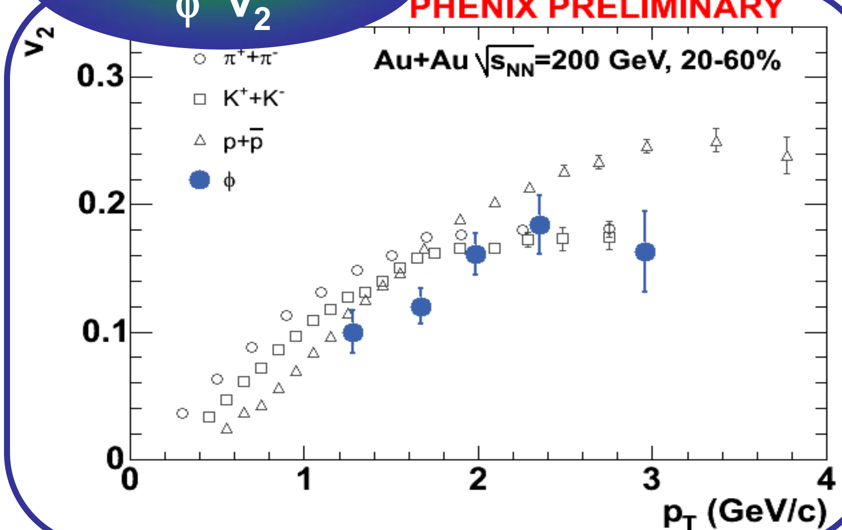
strongly coupled



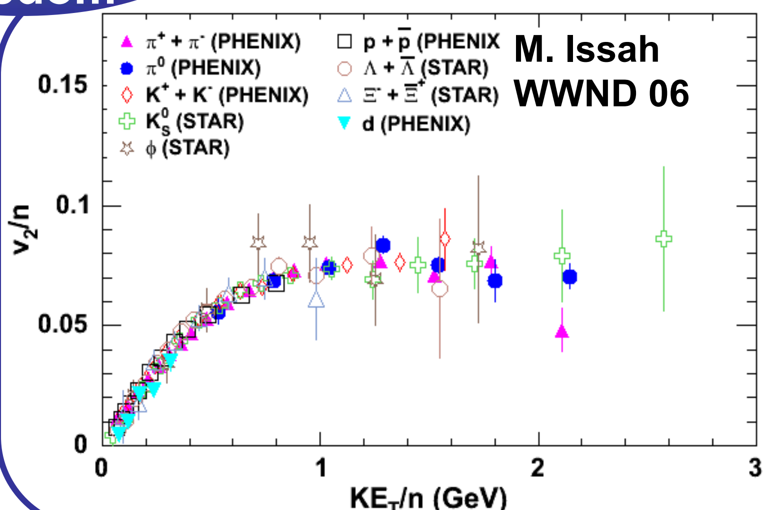
$$P = \rho^2 \left(\partial\varepsilon / \partial\rho \right)\Big|_{s/\rho}$$

Evidence for strongly interacting high energy density matter is compelling!

substantial ϕ v_2

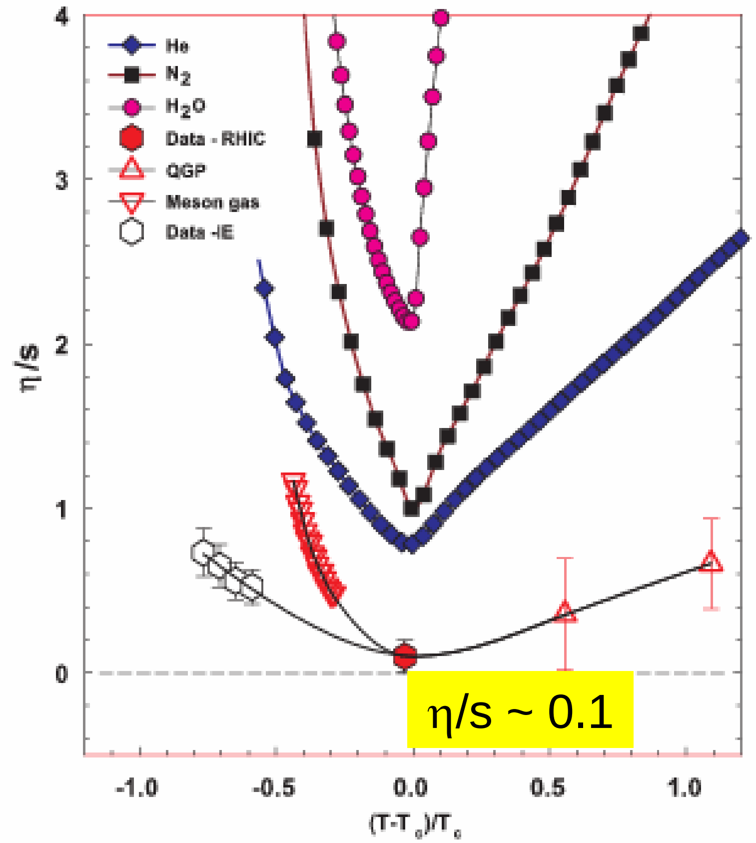


partonic degrees of freedom



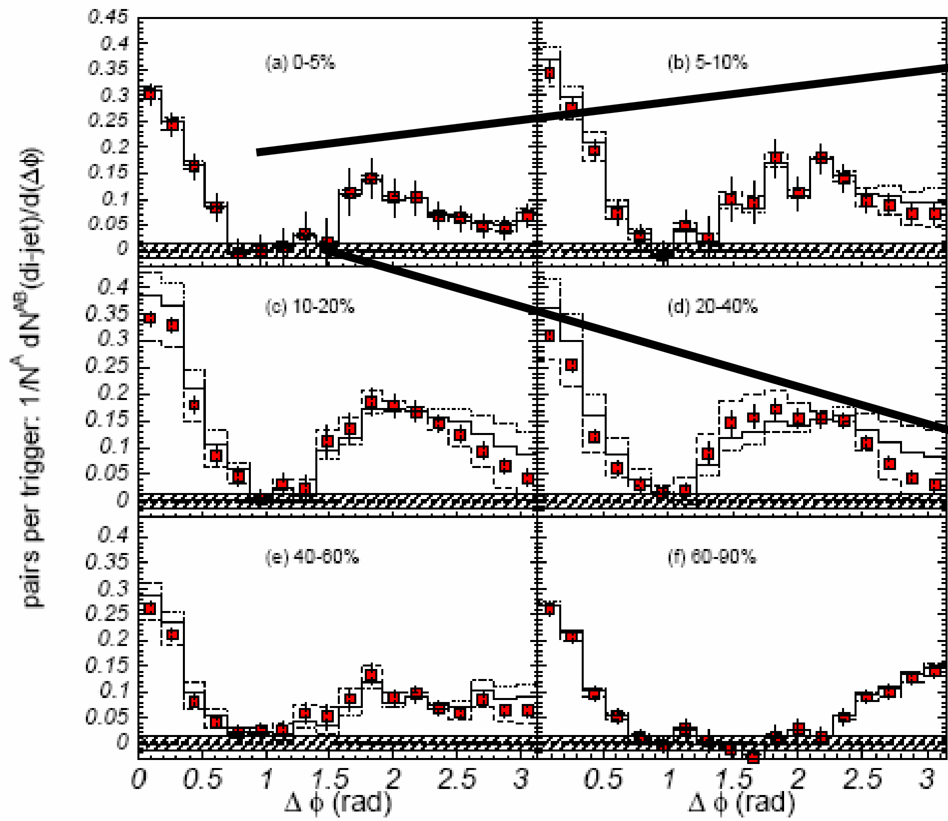
Shear Viscosity to Entropy Density Ratio

R. Lacey et al. Phys. Rev. Lett. 98,092301 (2007)

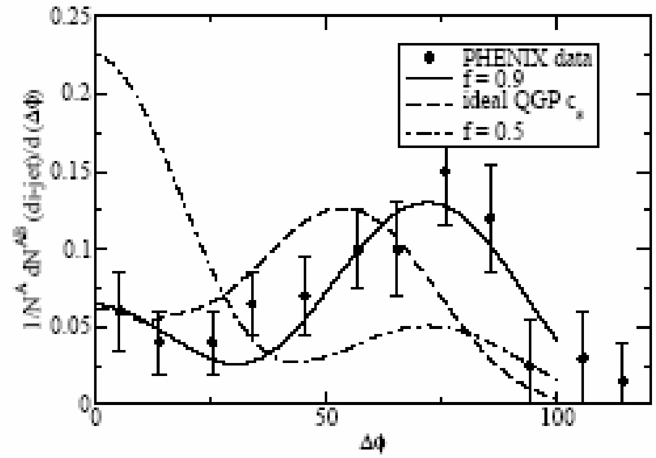


Bulk matter at RHIC exhibits characteristics of a strongly interacting partonic fluid with low viscosity to entropy density ratio: Observable medium response to jet likely

Do we see “Hints” of such a Medium Response?



PRL 97, 052301 (2006)



T. Renk, J. Ruppert
hep-ph/0509036

Strong centrality dependent modification of away-side jet in Au+Au

Can these correlation patterns be linked to medium response scenarios?

Possible mechanisms
mach-cone scenario

nucl-th/0406018 Stoecker
hep-ph/0411315 Casalderrey-Solana, et al

Not the only explanation:

Cherenkov gluon radiation: nucl-th/0507063
Koch, Majumder, X.-N. Wang

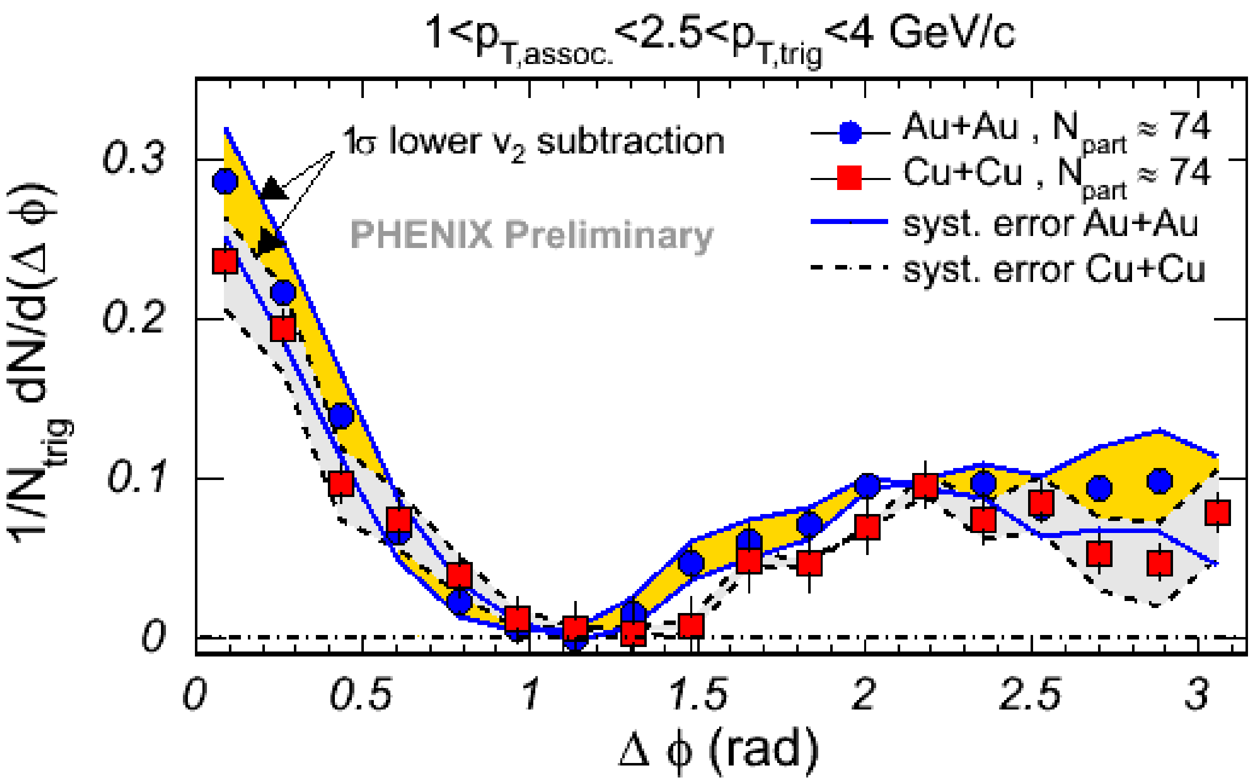
Jets and Flow couple: hep-ph/0411341
Armesto,Salgado,Wiedemann

What to expect of medium induced correlations?

Expect similar modification patterns for similar medium

-> test via centrality, beam energy
and system size dependence

System Size Dependence of Correlations



No strong system size dependence of correlation pattern observed within systematic errors (small yield differences due to path length effects?)

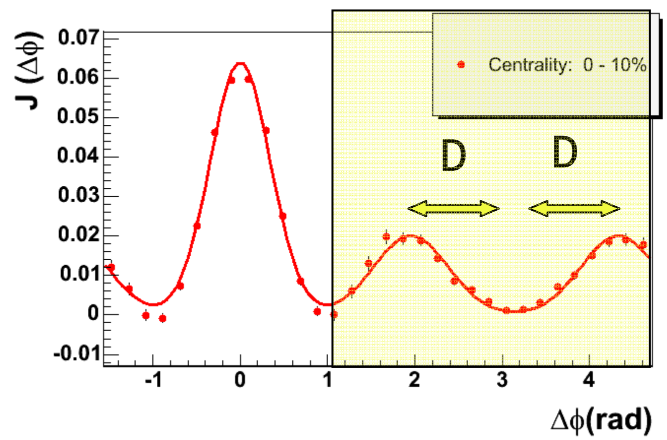
Let's take a closer Look at these Shapes

Characterize away-side shape via:

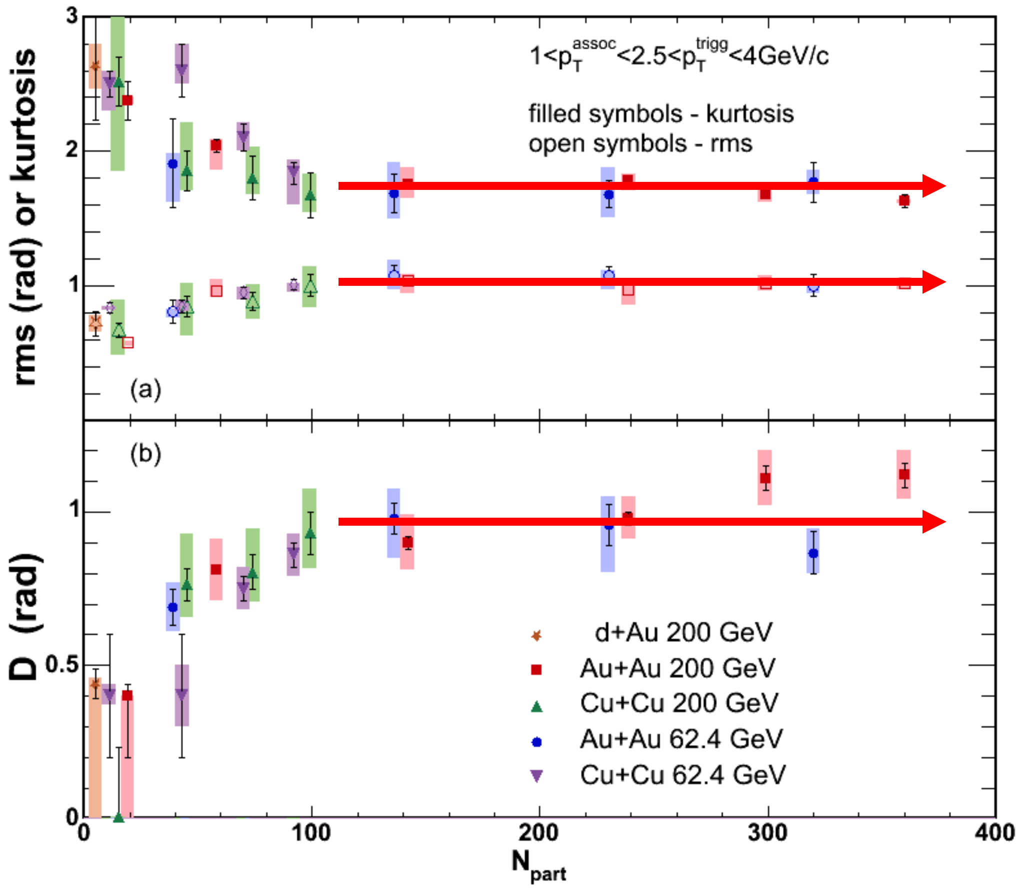
RMS : measures width of away-side peak

Kurtosis : $<(\Delta\phi-\pi)4>/RMS^2$, the 4th central moment, measures "gaussian-ness" of peak (= 3 for Gaussian)

D : distance between away-side peak and $\Delta\phi=\pi$ from double gaussian fit -> approximates peak-position

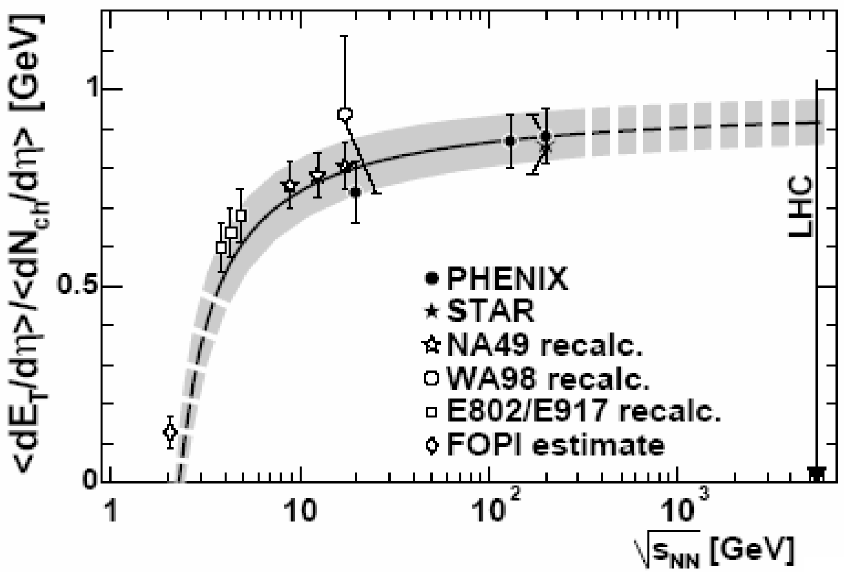


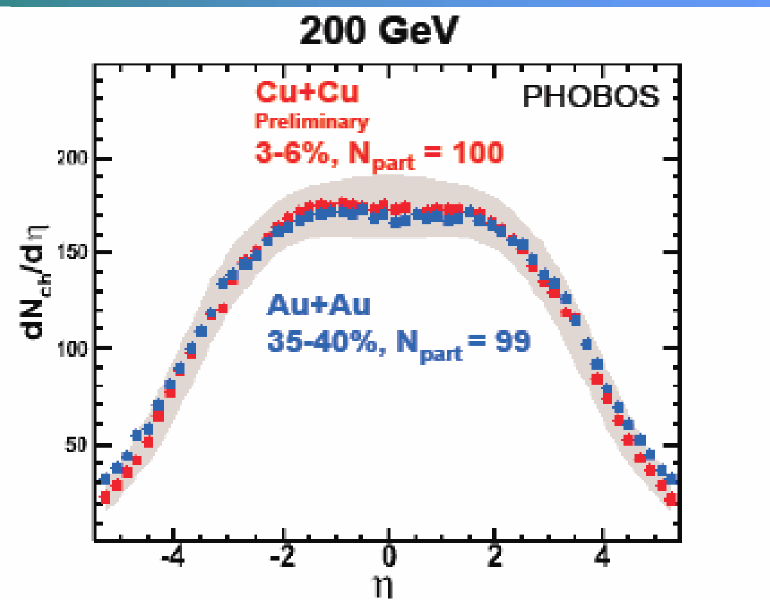
Energy and System Size Dependence of Shape Parameters

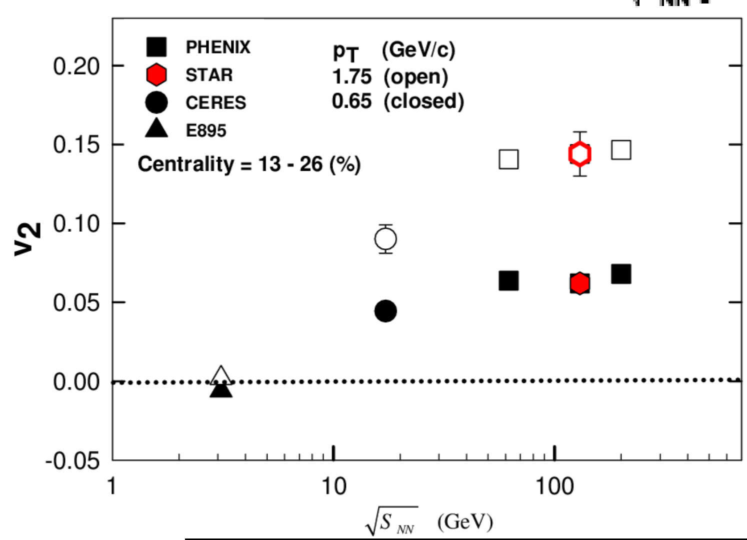


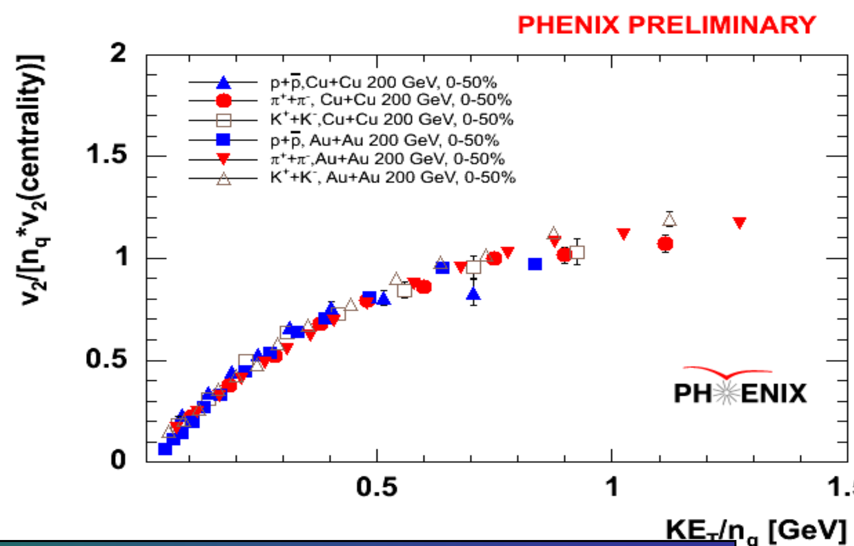
Shape modification largely independent of beam energy and system size in range root(s) ~ 62.4-200 GeV

But medium not too different over this range …









Consistent with intermediate pT shape modification being dominated by medium response to jet

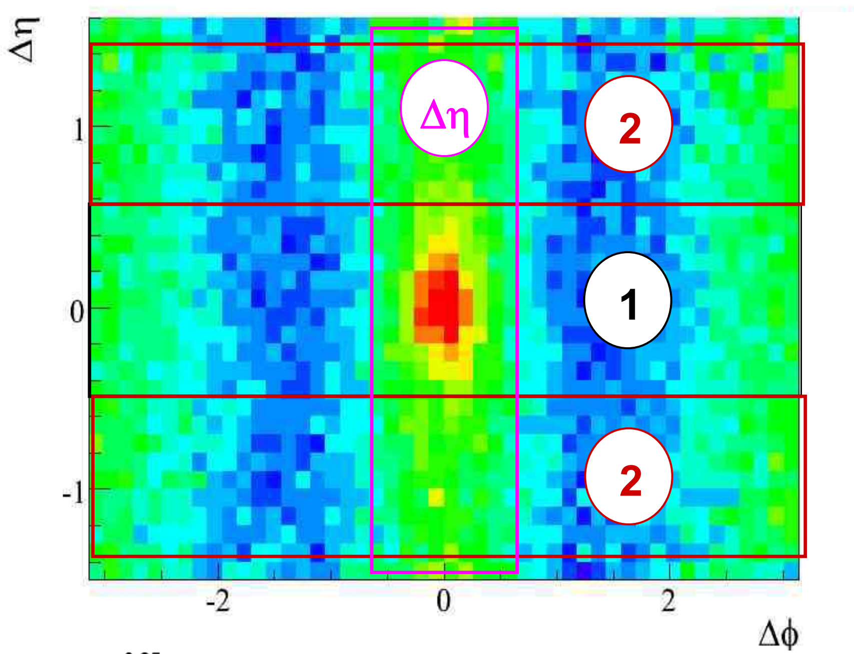
What about the near-side?

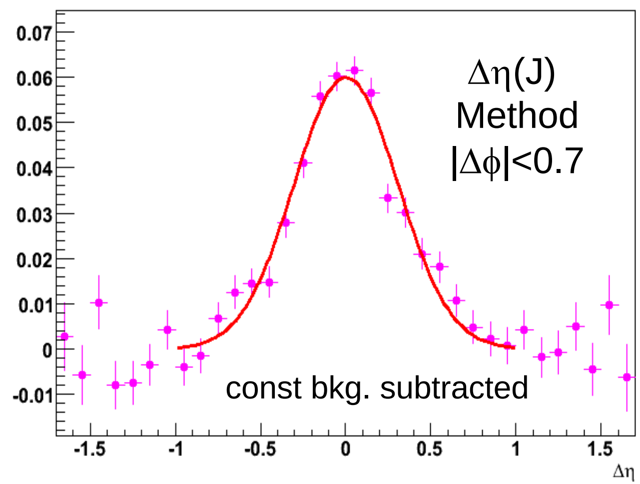
J. Putschke (STAR), PANIC 2006

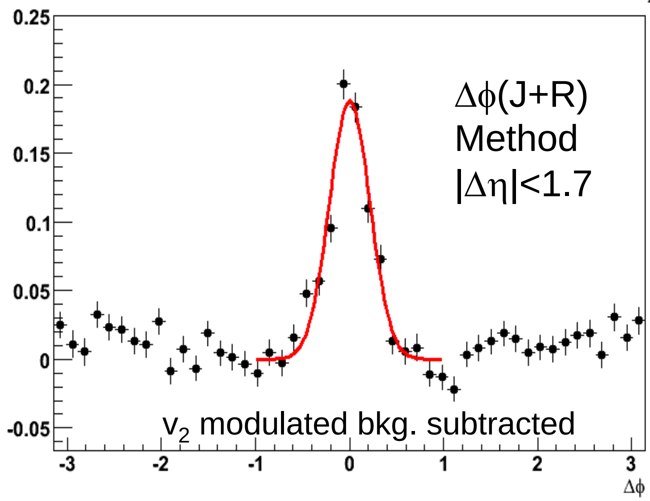
Au+Au 20-30%

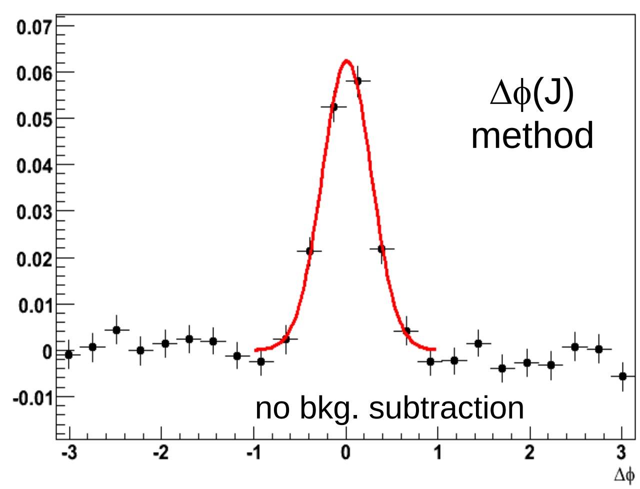
J = near-side jet-like corrl.

R = “ridge”-like corrl.



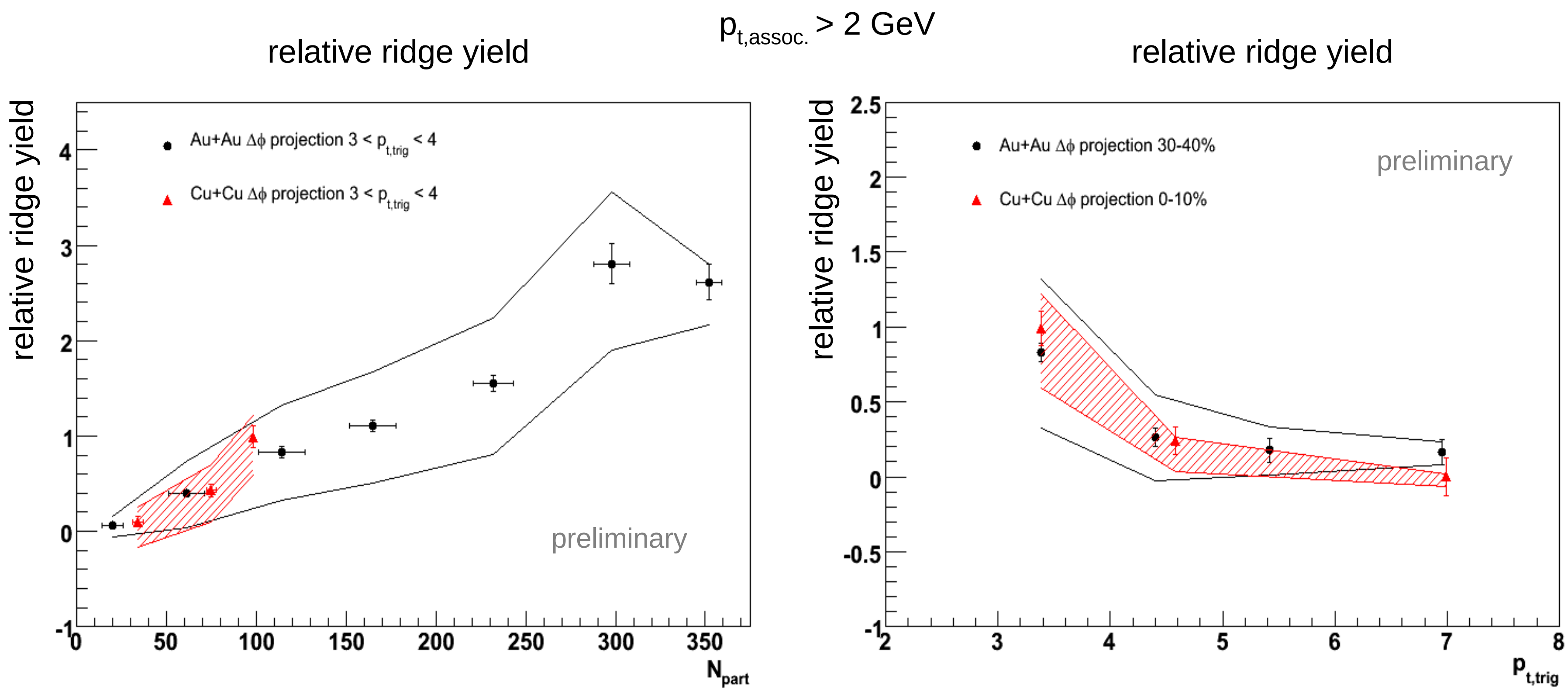






Centrality, pT and system size dependence

J. Putschke (STAR), PANIC 2006



Ridge yield important at intermediate p_T
Ridge yield in Au+Au and Cu+Cu comparable at same N_{part}
Similar trends as away-side correlation structures, similar origins?

Can we constrain the origin of the medium response?

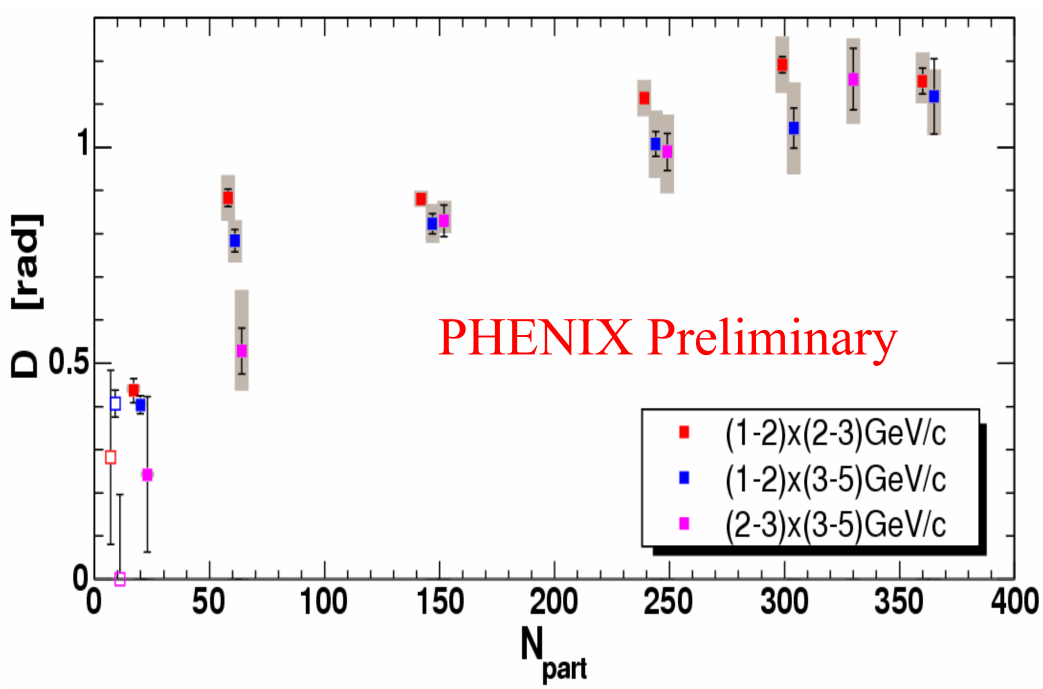
Differential Measurements / New Observables

-> pT dependence

-> particle composition in jets

-> unravel jet topologies via three-particle correlations

p_T Dependence of Shape Parameters



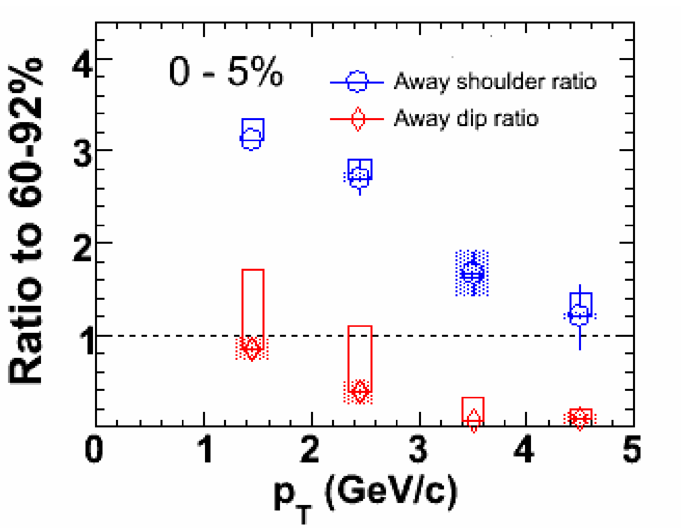
Weak pT dependence of peak angle poses challenges for early gluon Cherenkov radiation models which predicted a strong trend with pT

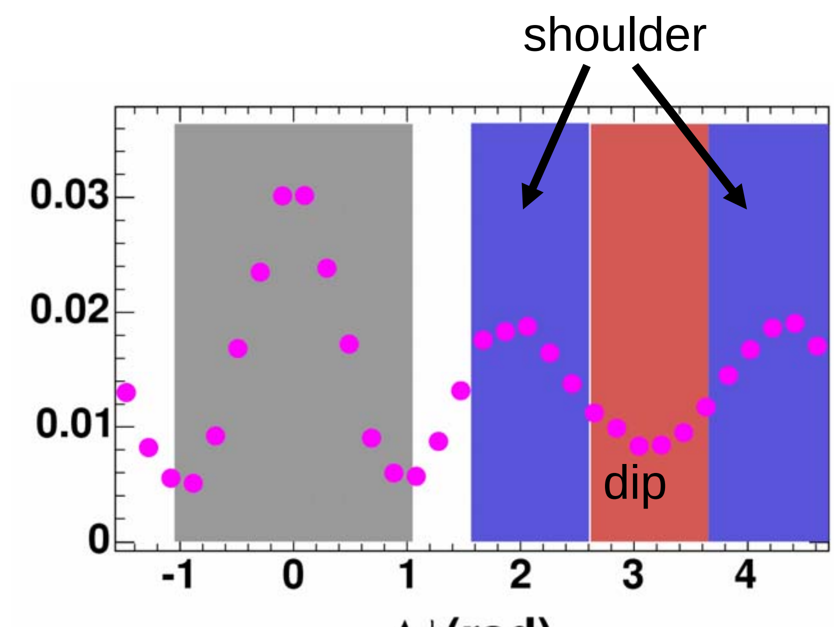
[1] Majumder, Wang, nucl-th/0507062
[2] Koch, Majumder, Wang, nucl-th/0507063

p_T Dependence of Yields

What if away-side correlation is combination of jet suppression and medium response?

$$I_{CP} = \frac{(PerTrigYield)_{cent}}{(PerTrigYield)_{peripheral}}$$

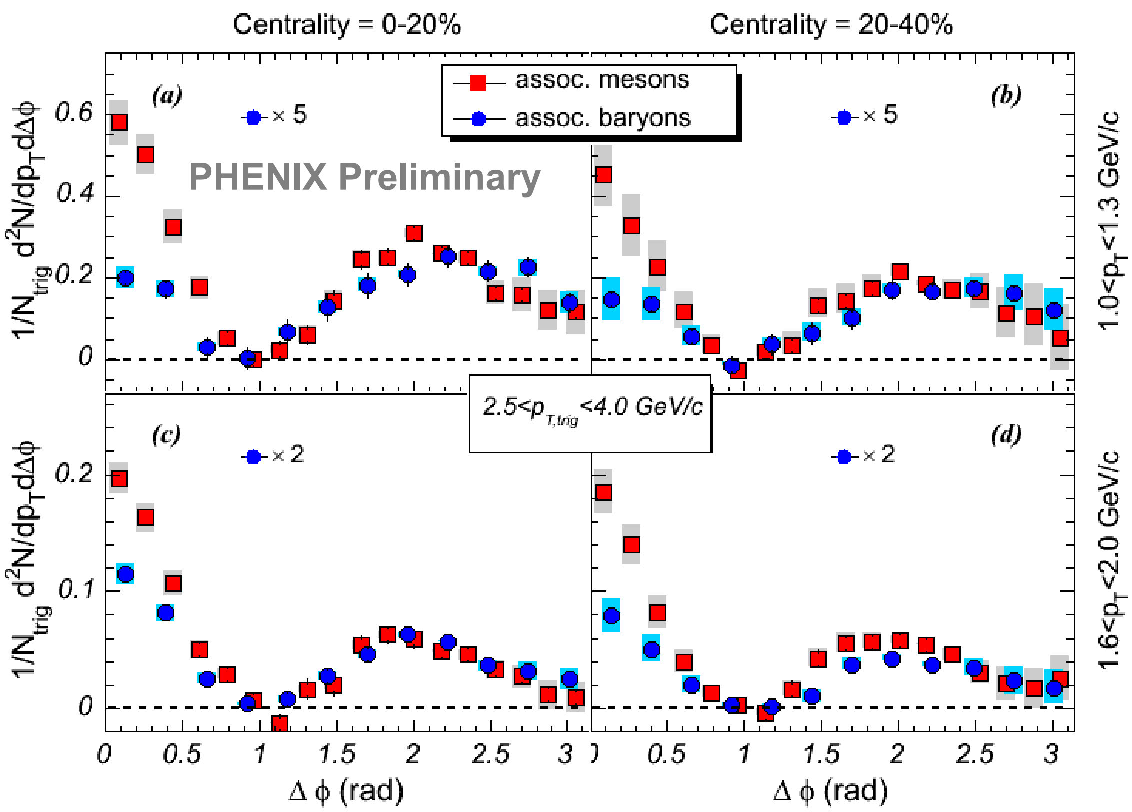




Yield in "dip" region strongly suppressed
Yield in "shoulder" region enhanced
Interplay of jet modification and medium response on away-side likely

Jet Associated Identified Particle Correlations

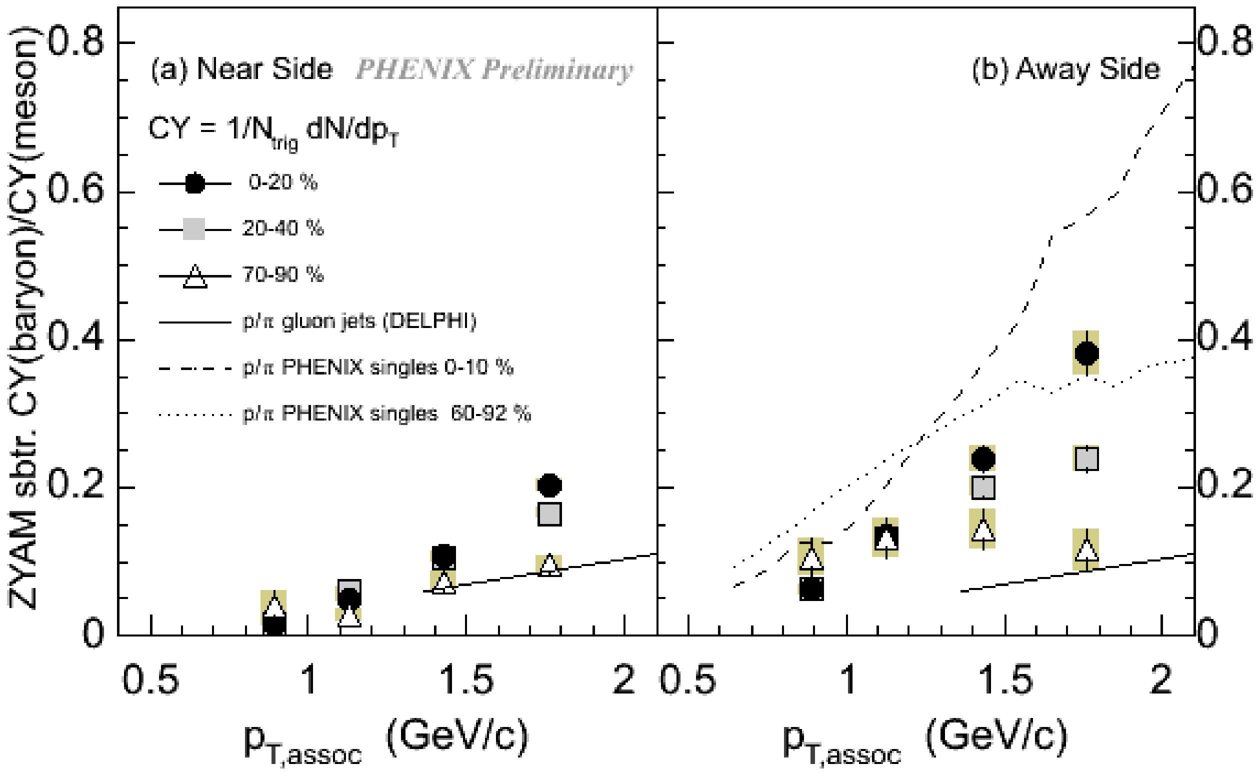
Meson vs. Baryon associated partner (for fixed Hadron trigger)



Jet associated mesons and baryons show similar shape modification

Jet Associated Baryon to Meson Ratio

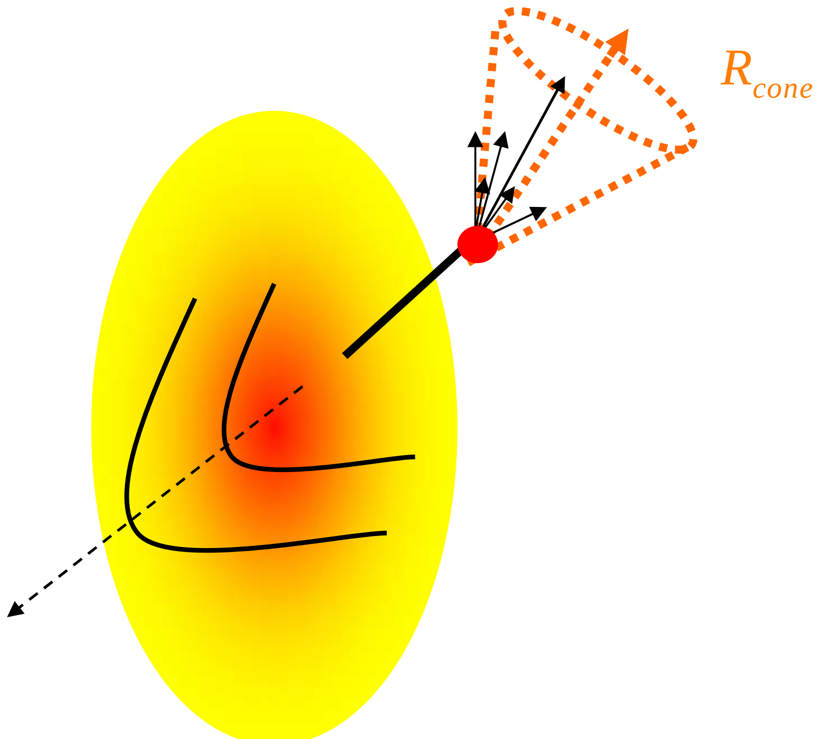
Meson vs. Baryon associated partner (for fixed Hadron trigger)



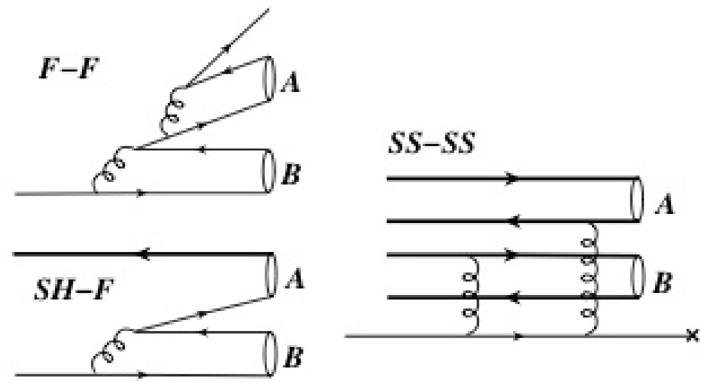
Centrality dependence seems inconsistent with vacuum fragmentation!

Centrality and pT dependence of jet associated baryon/meson ratio qualitatively similar to bulk matter: same mechanism ?

One Possible Scenario



Jet quenching can introduce 2-body correlations between the jet and the medium:



R. Fries, S. Bass and B. Mueller
nucl-th/0407102

Data not inconsistent with a scenario where partons from medium excitation "remember" jet direction. the jet and it's medium excitation are correlated.

So where do we stand… ?

Intermediate p_T away-side correlation structures are consistent with being dominated by medium response to jet.

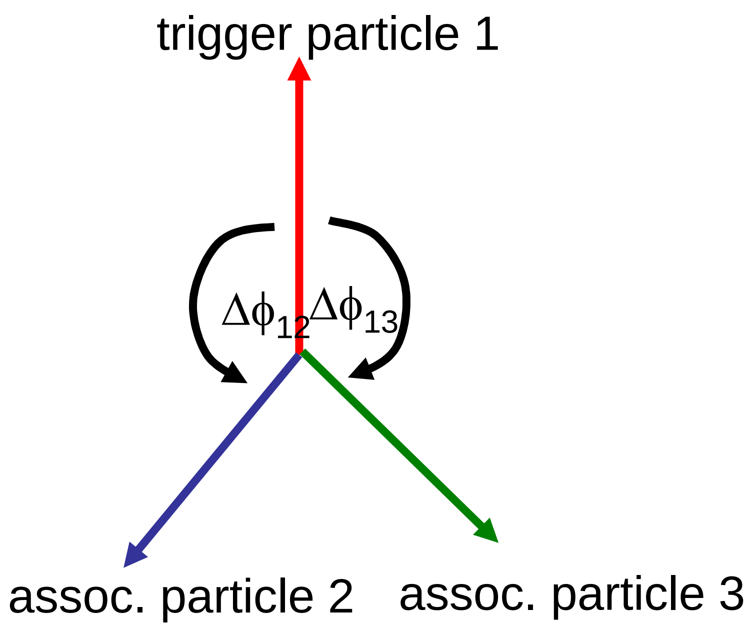
Centrality dependent rise of away-side baryon to meson ratio rules out modification conjectures that require the jets to fragment predominantly outside of the medium. Poses constraints on other models.

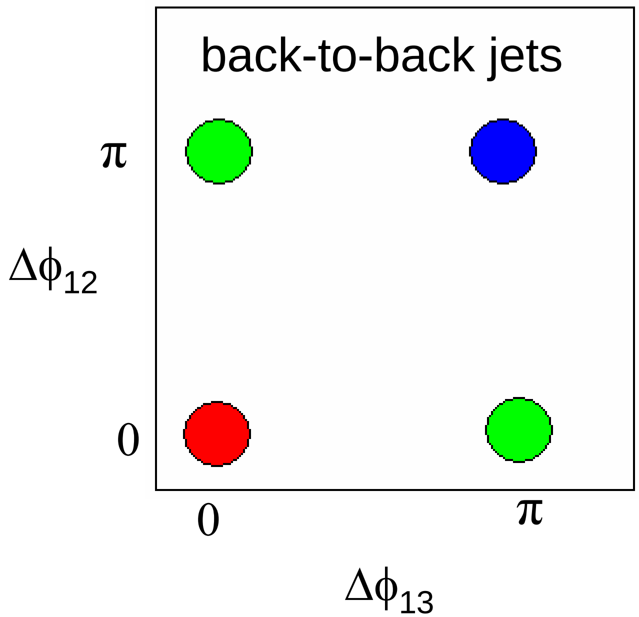
No clear distinction between deflected “wake” or mach cone from two particle correlations.

Need additional topological information:

3-particle correlations

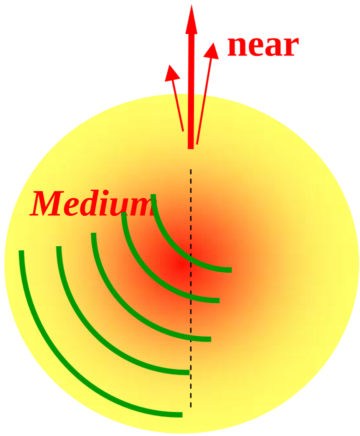
STAR Approach



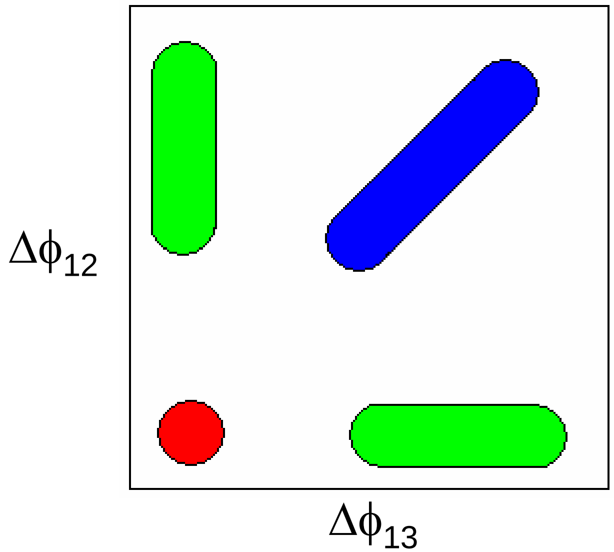


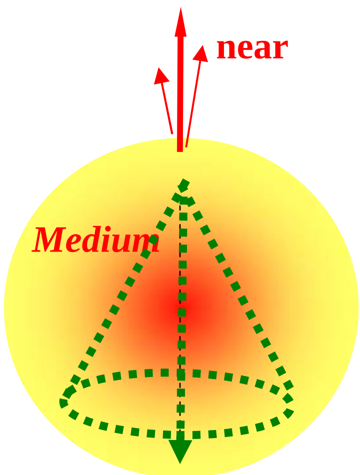
Look at azimuthal angle between (high pT) trigger particle and (lower pT) associated particles

Deflected versus conical medium response

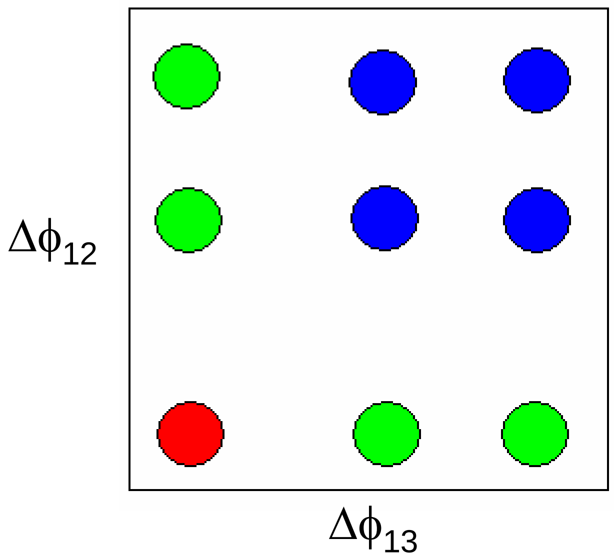


deflected medium excitation



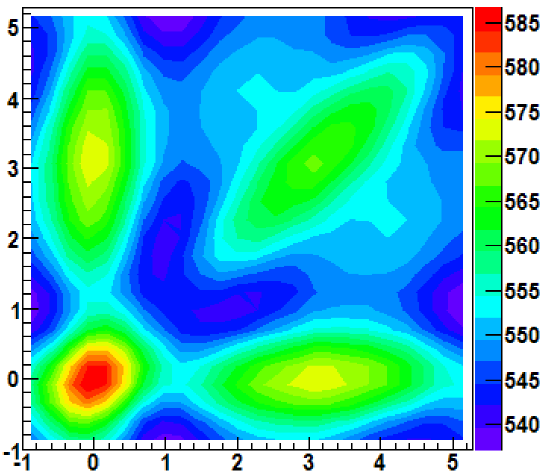


mach cone

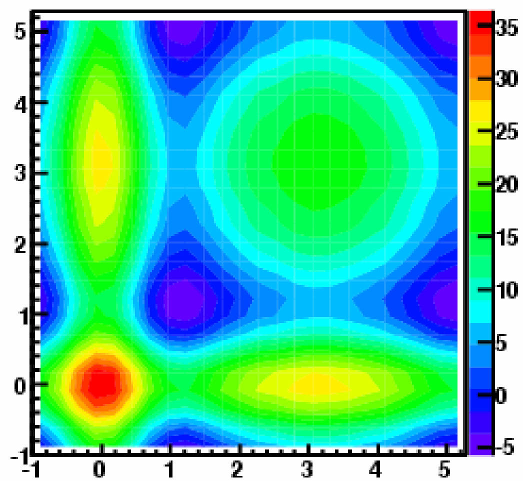


Data for 0-5% Au+Au

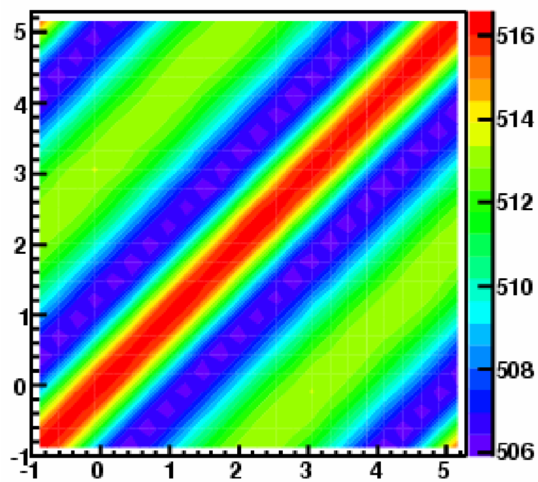
F. Wang (STAR) DNP Workshop 2006



raw

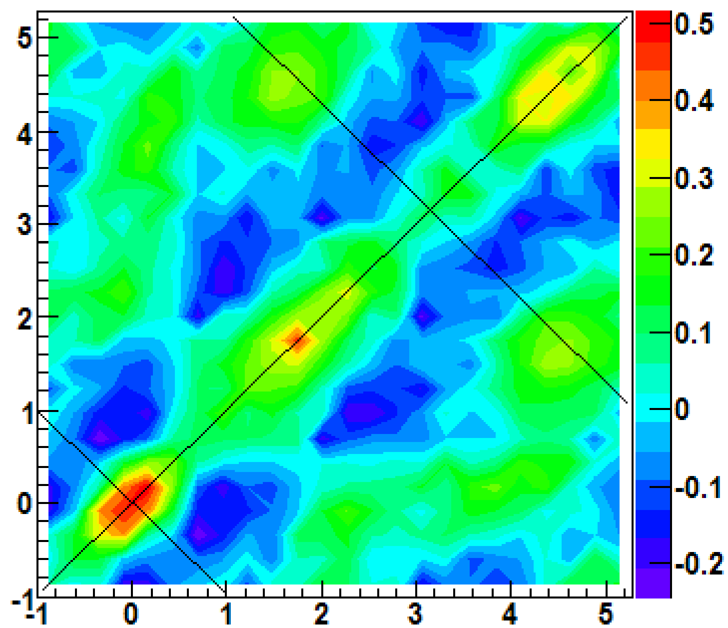


jet x bkgd



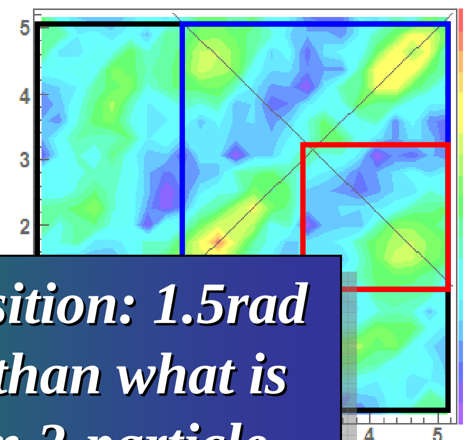
bkgd x bkgd

Off-diagonal correlation patterns consistent with mach cone. Cannot rule out some diagonal elongation



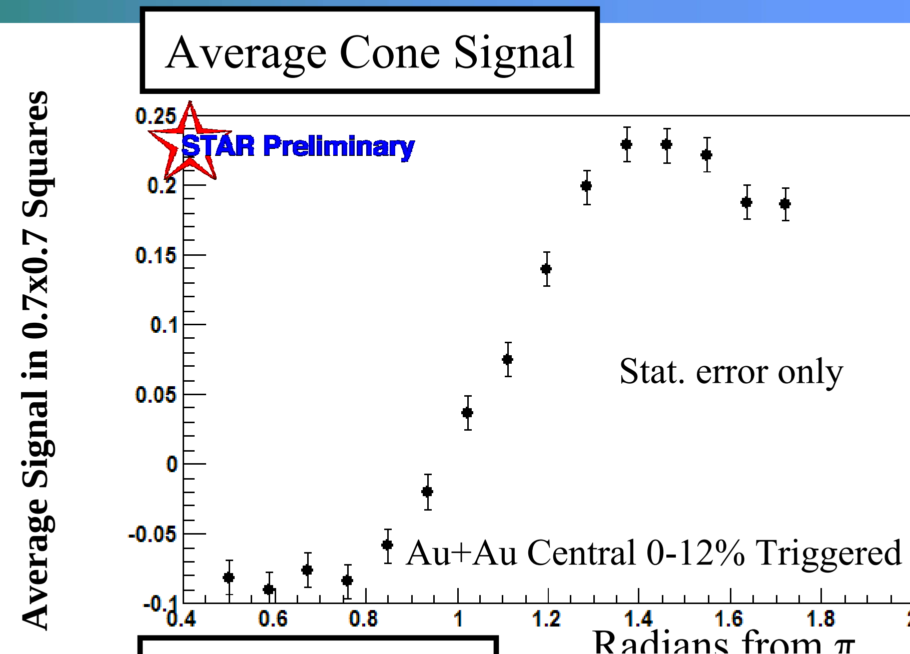
Cone Position ?

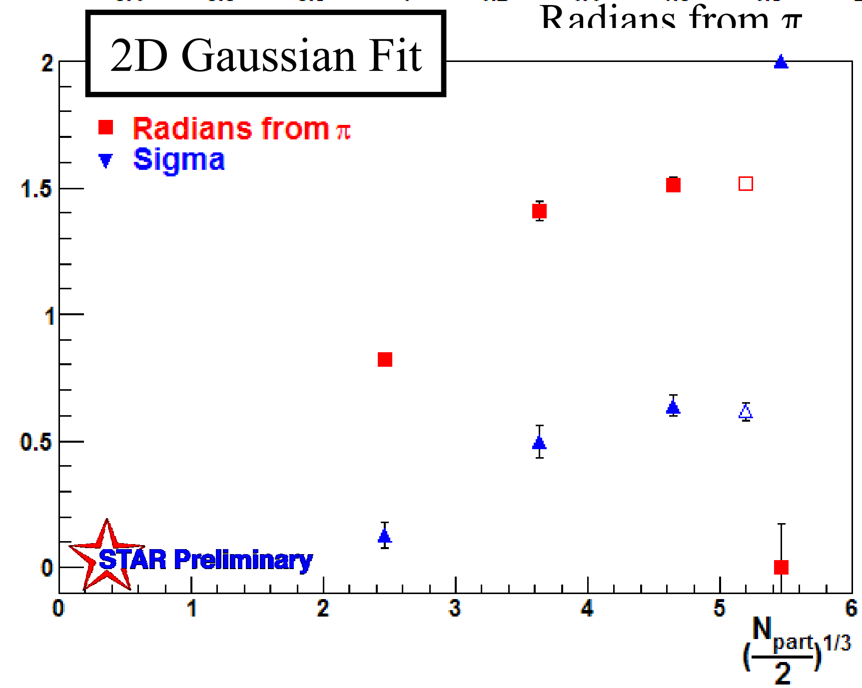
- Optimum placement of boxes can be determined from varying the placement and from fits.
- Fit fails for 0-10% Au+Au.
- 1.3 radians from π was chosen.



J.G. Ulery (STAR), Hard Probes 2006, nucl-ex/0609047.

Large peak position: 1.5rad (much larger than what is observed from 2-particle correlations (~ 1.1rad)





PHENIX Approach

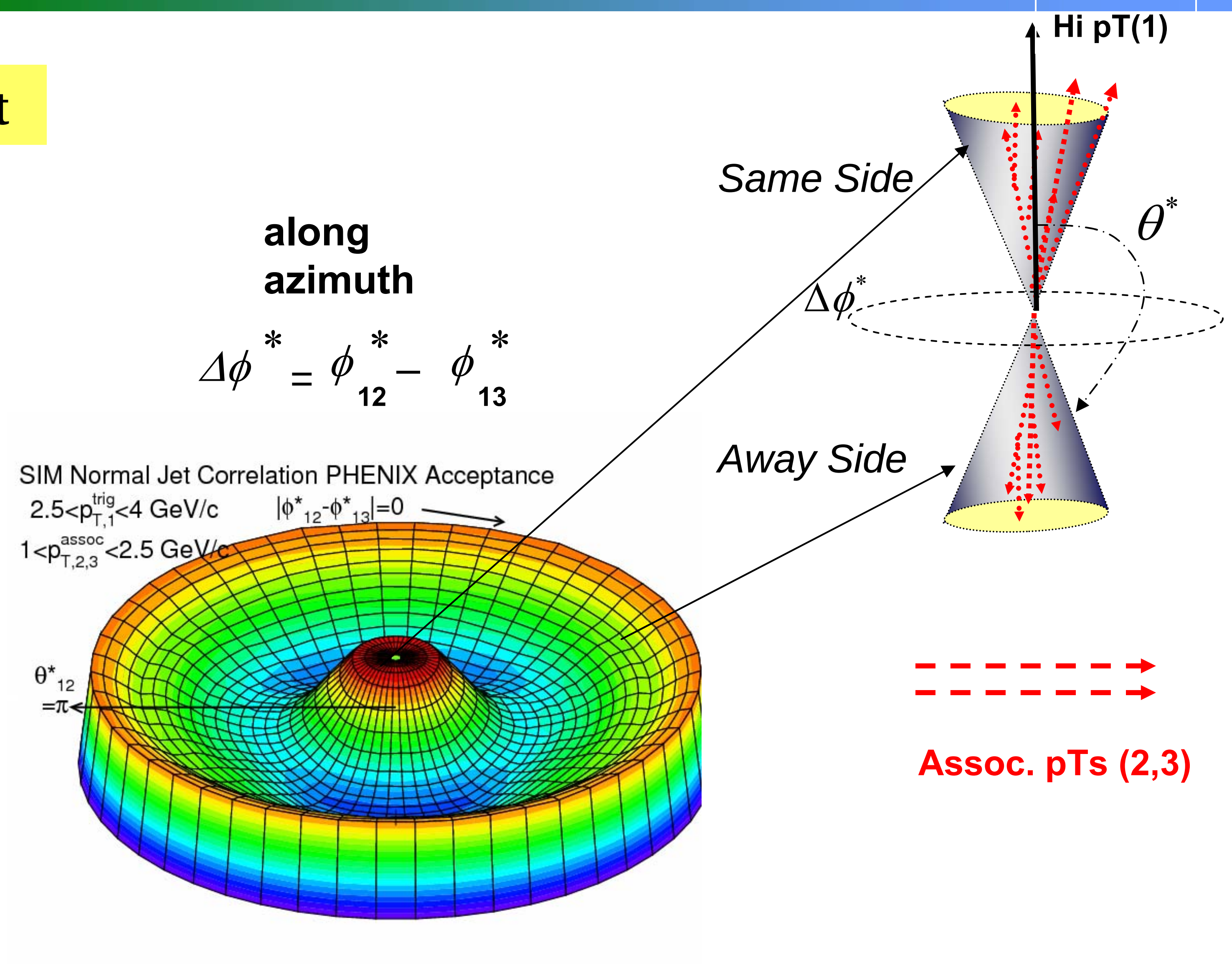
Polar plot

along azimuth

$$\Delta\phi^* = \phi^*_{12} - \phi^*_{13}$$

along radius

$$\theta^* = \theta^*_{12}$$

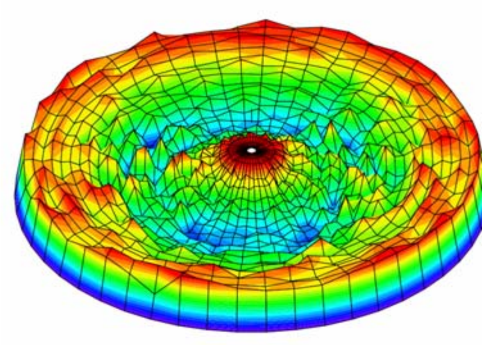


Normal Jet

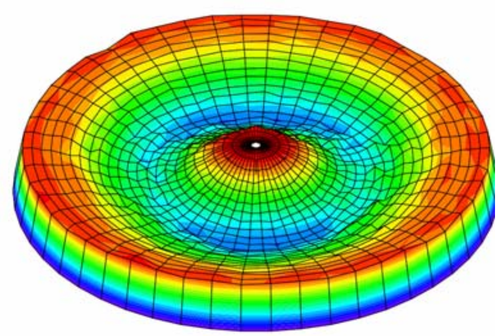
PHENIX Data (before background subtraction)

PHENIX *Preliminary*

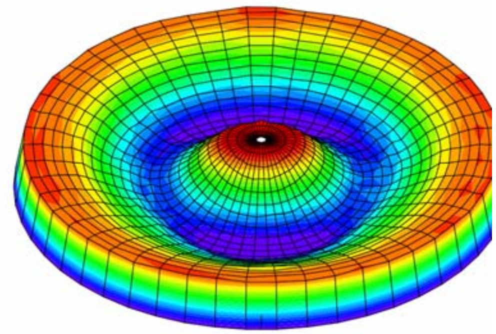
60-90 %



40-60 %

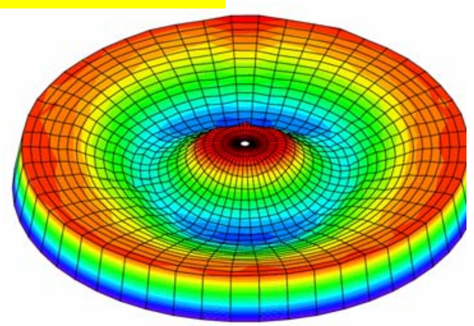


20-40 %

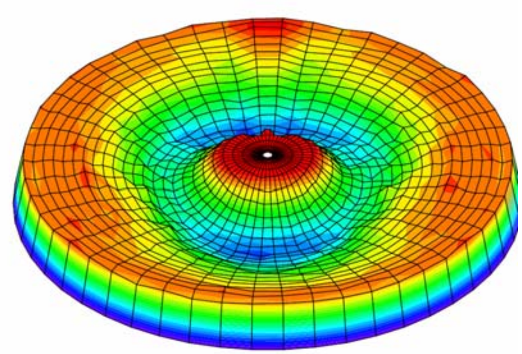


N. N. Ajitanand, LHC07 Workshop, Finland

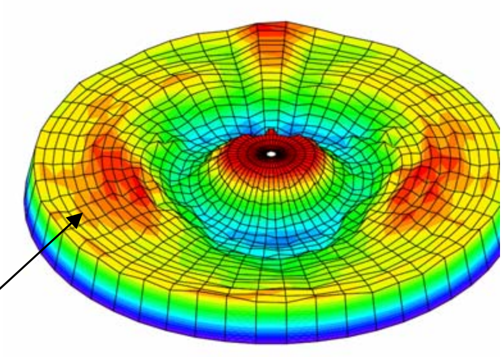
10-20 %



5-10 %



0-5 %

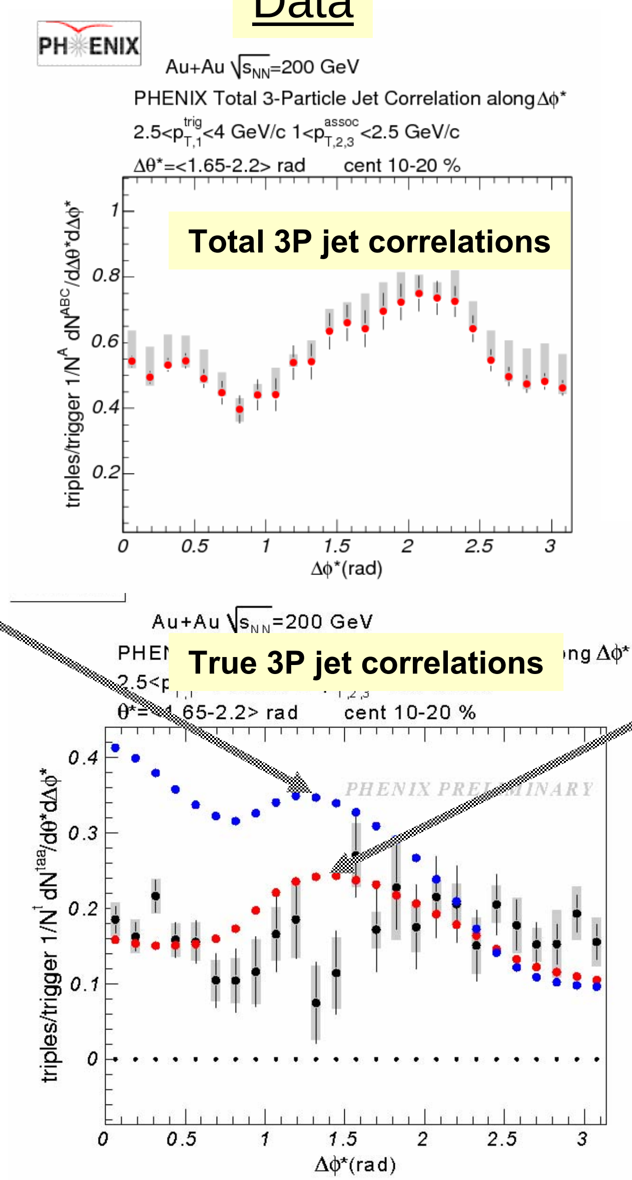


Important: Most central 3-particle correlation shows strong away-side modification BEFORE v2 subtraction

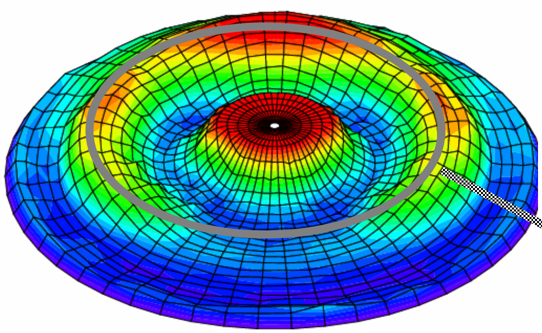
Deflected versus conical medium response

Azimuthal Sections

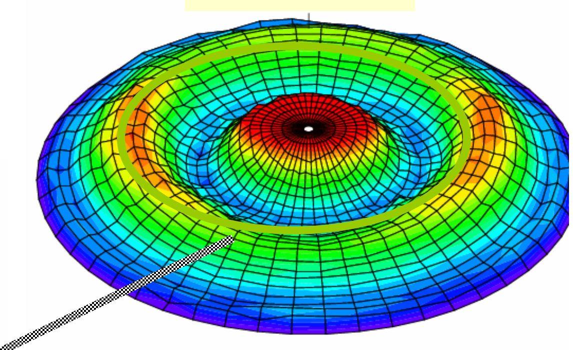
Data



Simulated Deflected jet



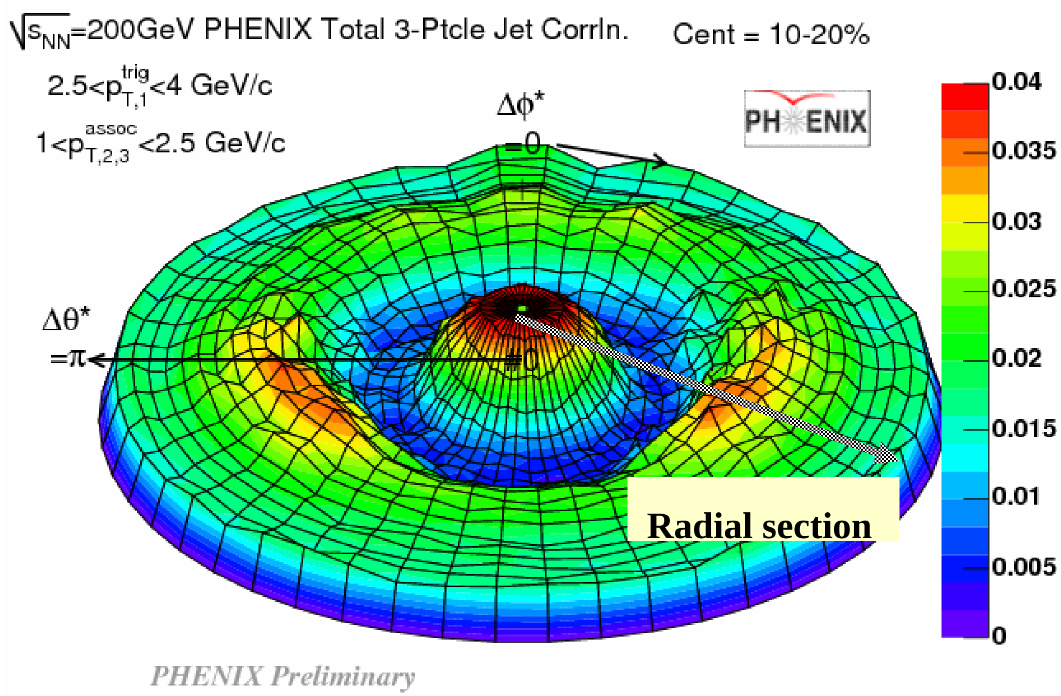
Simulated Mach Cone



Data consistent with mach cone expectations, but other contributions cannot be ruled out

N. N. Ajitanand, LHC07 Workshop, Finland

Cone Position ?



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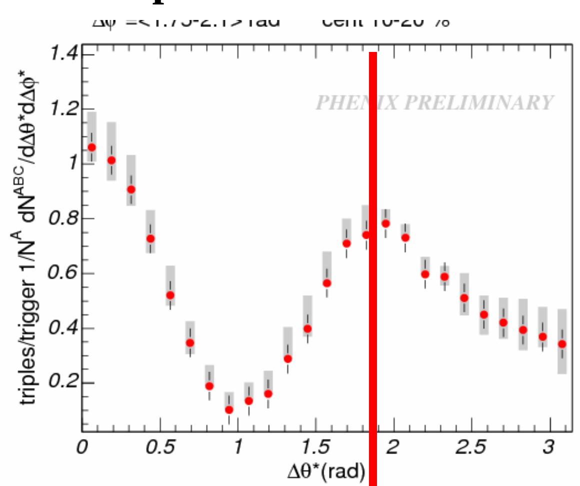
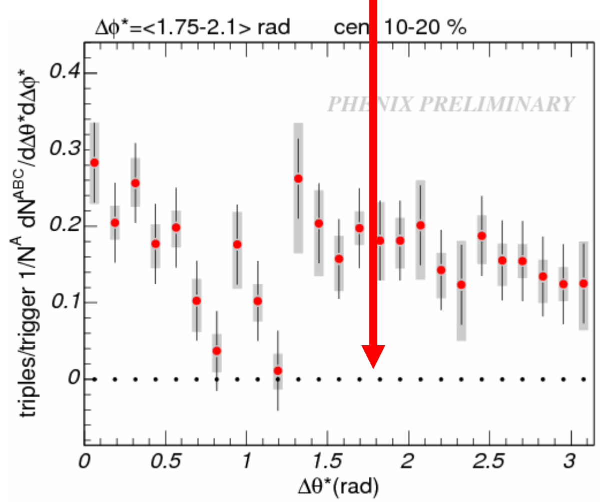
Large errors, but would conclude smaller cone position (1.2rad off π) than STAR?

Total 3-particle Jet Correlation



True 3-particle Jet Correlation



What do 3-particle correlations tell us?

Both experiments (STAR and PHENIX) observe correlation patterns that are consistent with conical flow but other contributions to true 3-particle correlations cannot be ruled out.

Quantitative analysis is difficult and extraction of peak position is complicated

High statistics RUN7 data should allow additional handle on systematics for quantification of the observed signals.

… we live in exciting times :-)

Summary and Conclusion

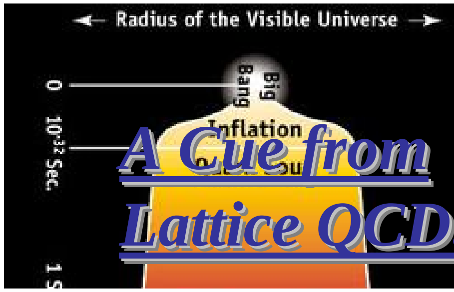
- *Strong modification of away-side peak is reflected in 2-particle correlations. Systematic trends consistent with medium response to jet*

- *Particle composition of away-side correlation signal is inconsistent with vacuum fragmentation, but shows similar trends as the bulk matter. This can be qualitatively understood in a recombination model where the medium excitation and the jet direction are correlated*

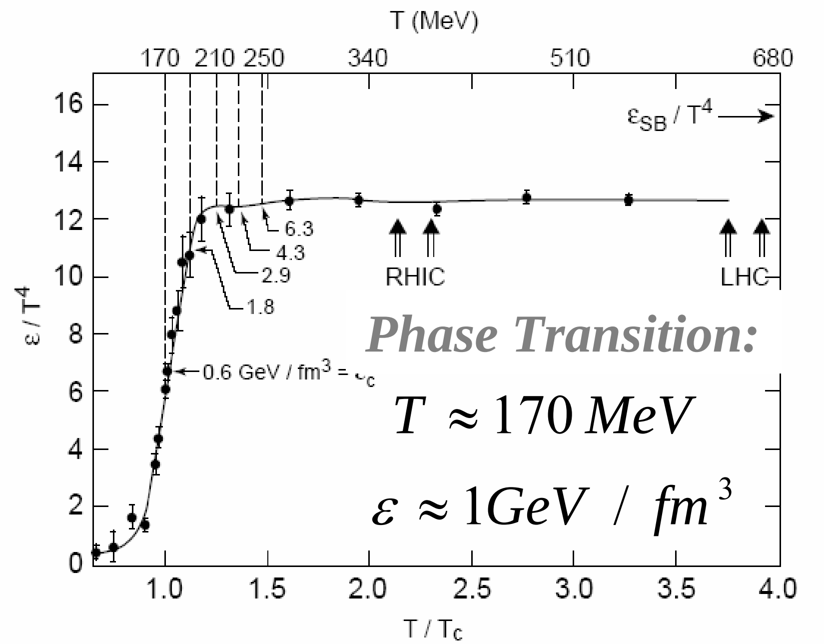
- *Three particle correlations are consistent with mach cones, but cannot rule out other contributions, as well.*

- *The response of the medium to the jet is as important for characterizing the QCD matter at RHIC as the response of the jet to the medium.*

Backup Slides



A Cue from Lattice QCD:



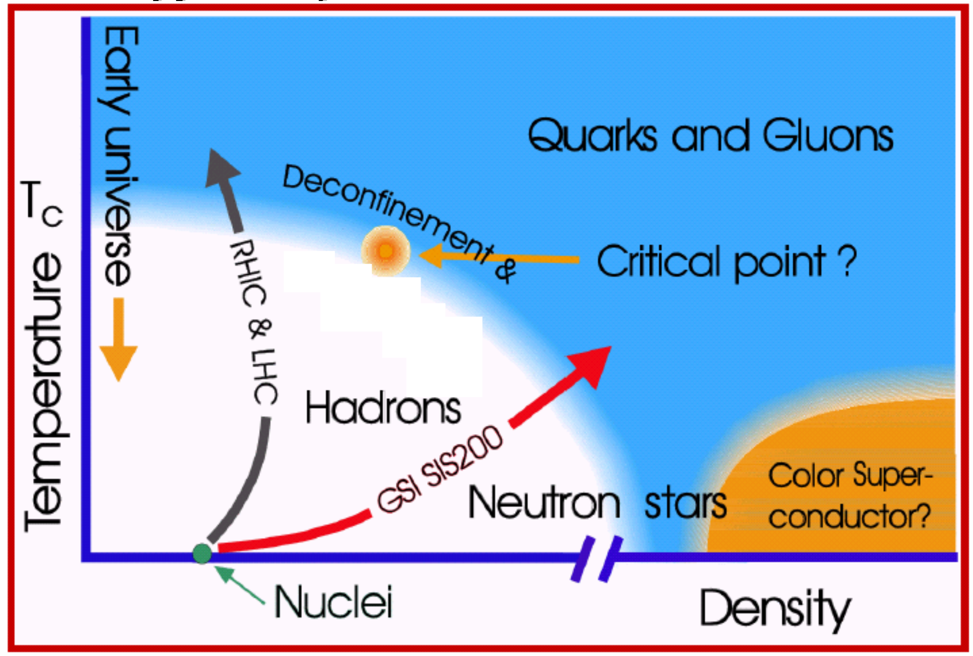
Phase Transition:

$$T \approx 170\ MeV$$

$$\varepsilon \approx 1 GeV\ /\ fm^3$$

Today's Cold Universe

Phase Diagram for Nuclear Matter



Can we learn about the history of the universe from Heavy Ion Collisions?

Decomposition of Flow and Jet Signals

Subtraction

N.N. Ajitanand et al.
Phys. Rev. C 72, 011902 (2005)

Extinction

Two source model : Flow (H) & Jet (J)

$$\overbrace{C(\Delta\phi)}^{Correlation\ Function} = a_0\left[\overbrace{H(\Delta\phi)}^{Harmonic} + \overbrace{J(\Delta\phi)}^{Jet\ Function}\right]$$

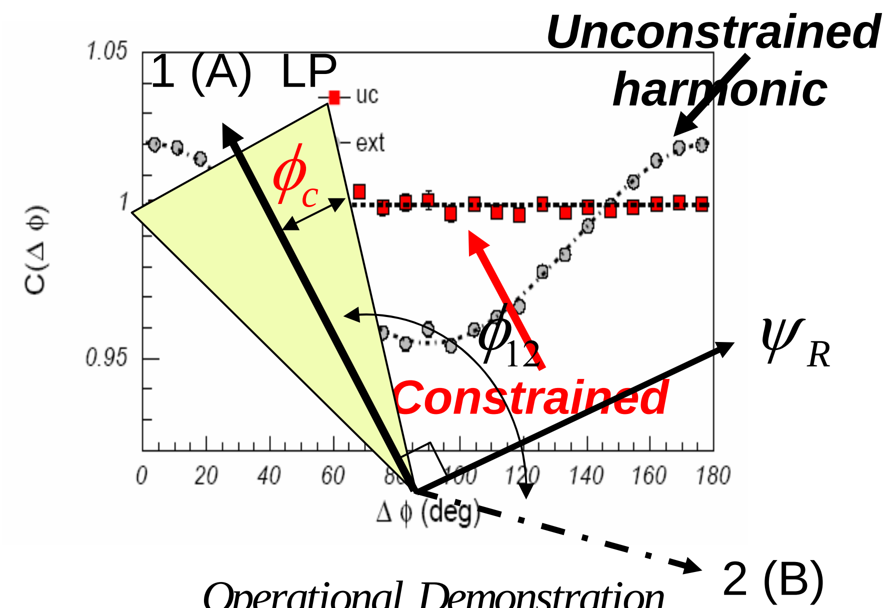
$$\overbrace{J(\Delta\phi)}^{Jet\ Function} = \frac{\left[C(\Delta\phi) - a_0 H(\Delta\phi)\right]}{a_0}$$

a_0 is obtained without putting any constraint on the Jet shape by requiring

$$J(\Delta\phi_{\min}) = 0$$

i.e. Zero Yield At Minimum (ZYAM)

High pt particle constrained perpendicular to RP



Operational Demonstration

vary $\Delta\phi_c$ Constraint byte

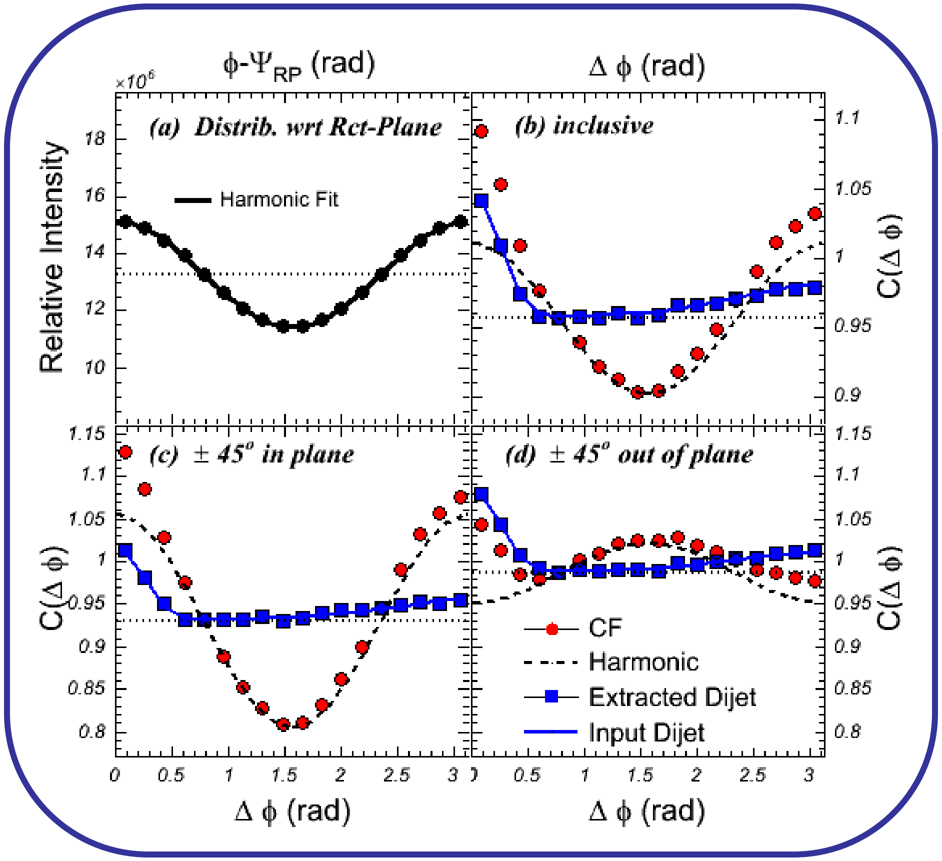
untill $v_2^{out} \sim 0$

Reliable Decomposition of Flow and Jet Signals via two separate Methods

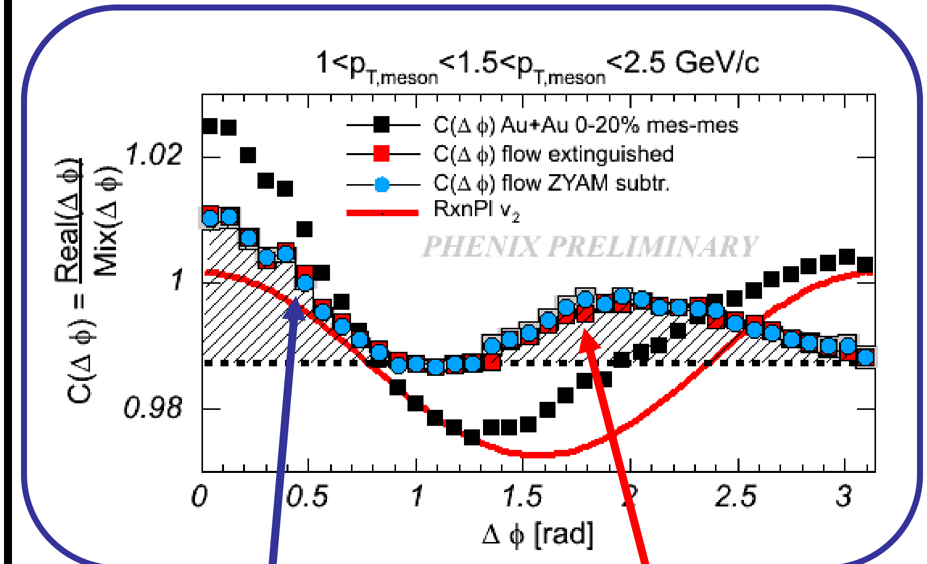
Test of Ansatz

Simulation

Phys. Rev. C 72, 011902 (2005)



Data



ZYAM subtracted $J(\Delta\phi)$

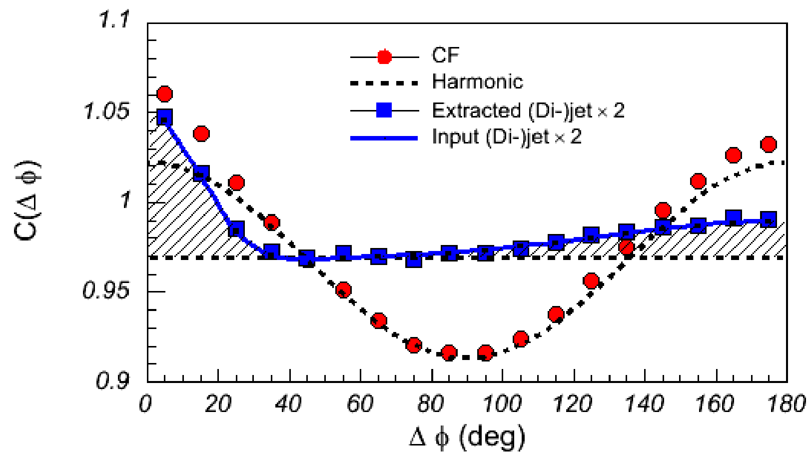
Flow extinguished $C(\Delta\phi) = J(\Delta\phi)$

Both Methods Agree!

Strong Away-Side Modification in Au+Au Revealed via Both Methods

Two Source Model

$$\overbrace{C(\Delta\phi)}^{\text{Correlation Function}} = a_0 \left[\overbrace{H(\Delta\phi)}^{\text{Harmonic}} + \overbrace{J(\Delta\phi)}^{\text{Jet Function}} \right]$$



Jet-Pair Fraction:

$$JPF = \sum a_0 J(\Delta\phi) / \sum C(\Delta\phi)$$

Efficiency corrected Conditional yield (CY):

$$CY = JPF \times \frac{n_t^{AB}}{n_t^A \times n_t^B} \times n_t^B$$

n_t^{AB} → **Eff. Corrected pair rate**

$n_t^A \times n_t^B$ → **Eff. Corrected Singles yields**

Efficiency corrected Conditional yield (CY):

$$CY = JPF \times \frac{n^{AB}}{n^A \times n^B} \times n_t^B$$

$\frac{n^{AB}}{n^A \times n^B}$ → **Recorded values**

Three Particle Correlations

See N.N. Ajitanand's talk

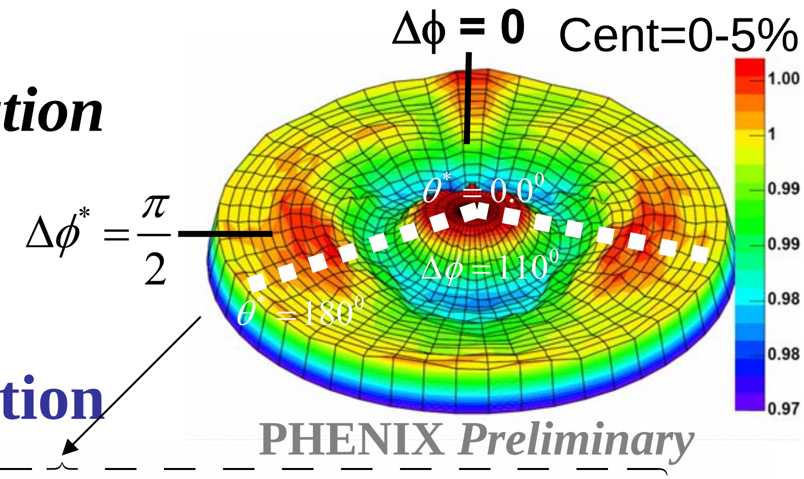
3-particle Correlation Function

$2.5 < p_T^{trig} < 4.0$ GeV/c

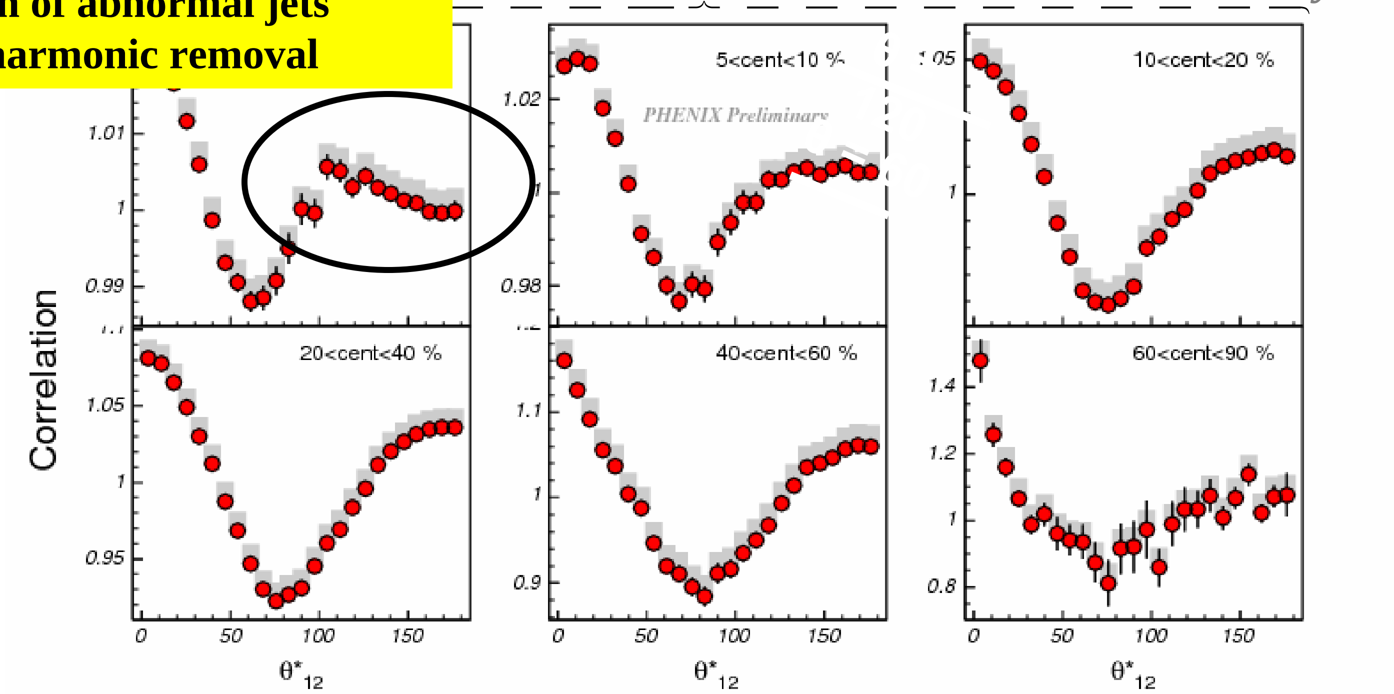
$1.0 < p_T^{assoc} < 2.5$ GeV/c

PHENIX Acceptance

Uncorrected, NO v_2 subtraction



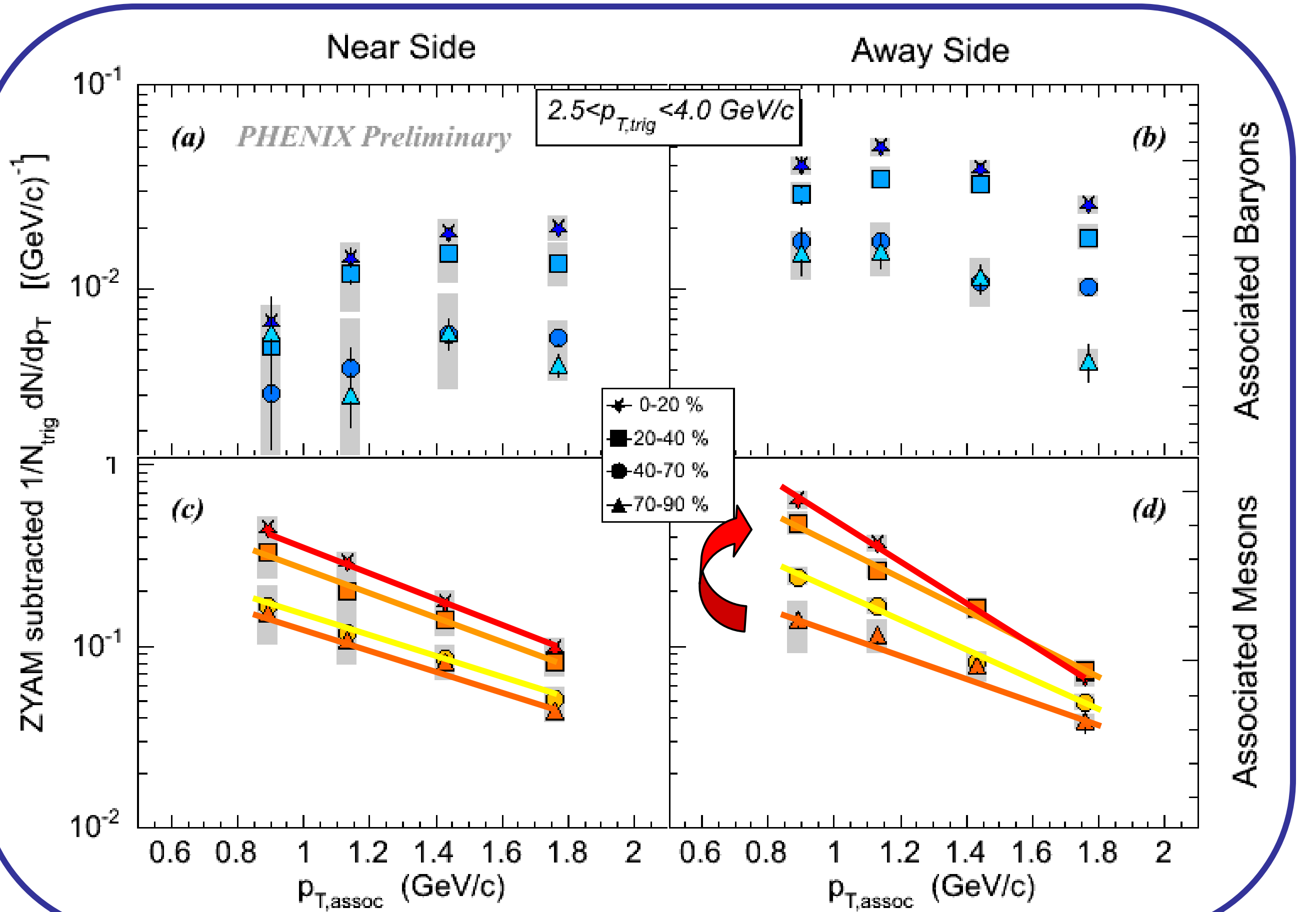
Indication of abnormal jets without harmonic removal



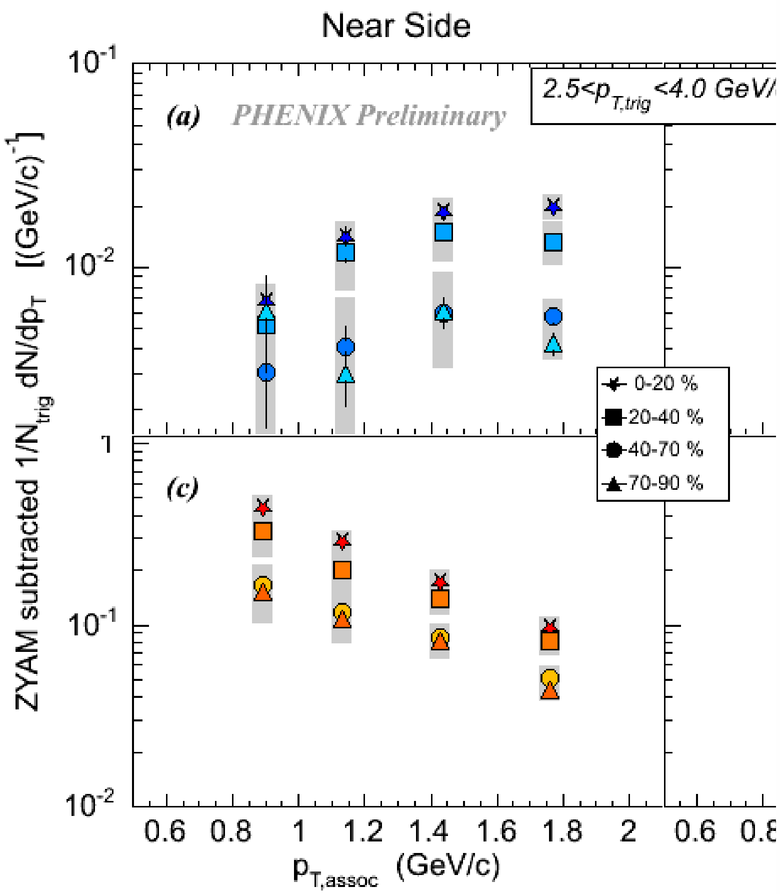
Further study needed to distinguish between cone or deflected jets

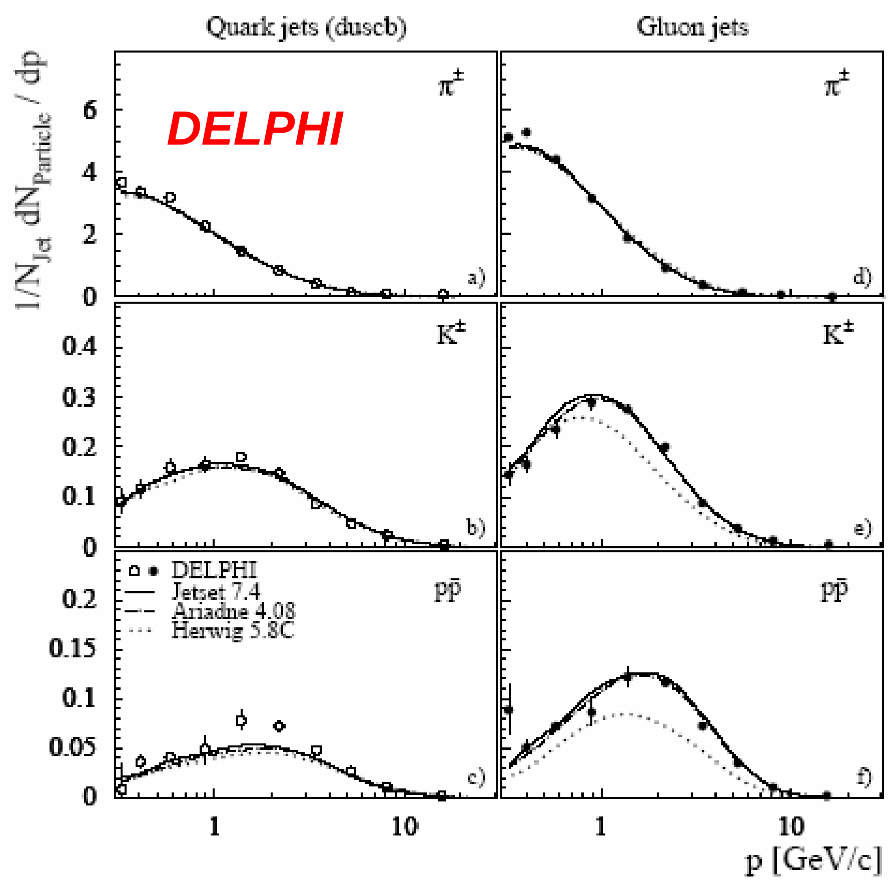
Jet Associated Identified Conditional Yields

Meson vs. Baryon associated partner (for fixed Hadron trigger)



Different p_T trends of associated meson and baryon yields



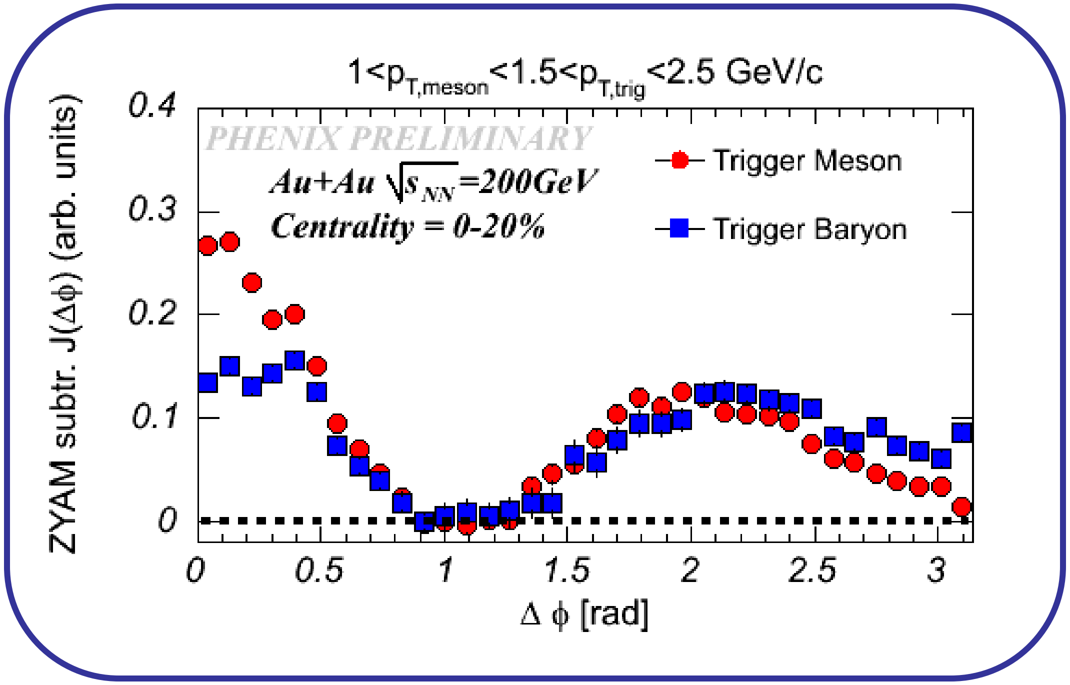


Baryon yield dependence consistent with jet physics in e-e collisions

Figure 5: Momentum spectra of identified hadrons in quark and gluon jets a)-c) spectra of pions, kaons, and protons in quark jets; d)-f) corresponding spectra for gluon jets in events with Y topology. The predictions of the generator models JETSET, ARIADNE und HERWIG are drawn as lines.

Fully Identified Jet Functions

Meson vs. Baryon trigger (for fixed Meson partner)

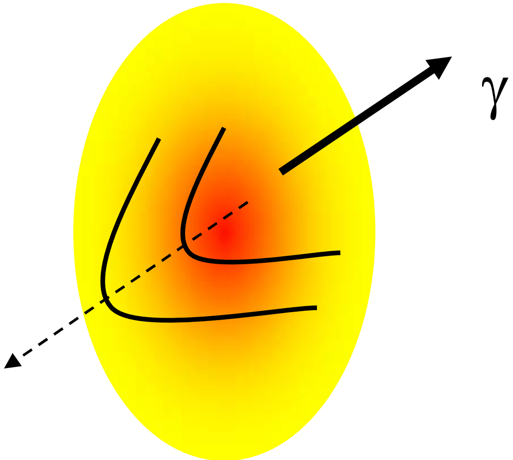


Trigger particle species dependent jet modification at intermediate p_T ?

Can we do energy calibrated studies of the medium response?

- Normal dijet (π^o-h):
  - Trigger bias: $E_\pi < E_{jet,}$, <z>~0.75
  - Possible surface bias
- Direct γ tagged jet:
  - No fragmentation: $E_\gamma \sim E_{jet}$
  - No strong interaction, sensitive to the whole medium

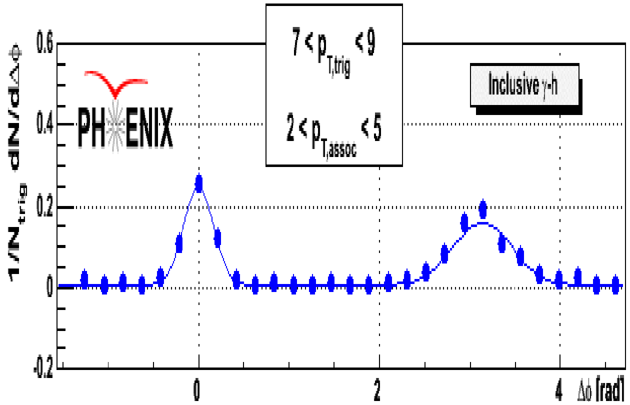
Proposed in hep-ph/9605213 ~10 years ago



Fix maximum jet energy that can be transferred to the medium, check for consistency in medium response.

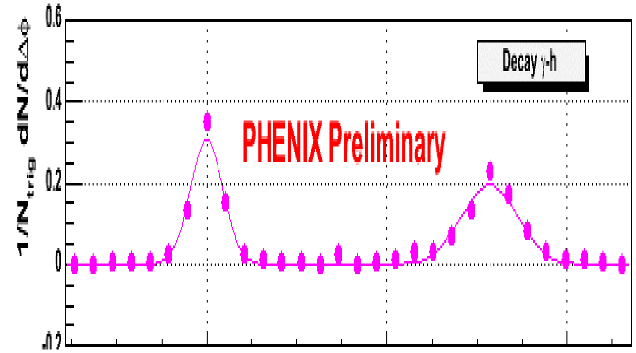
Methodology in a Nutshell

❶ *generate incl. γ-h per trigger yield*



❷ *generate decay γ-h per trigger yield*

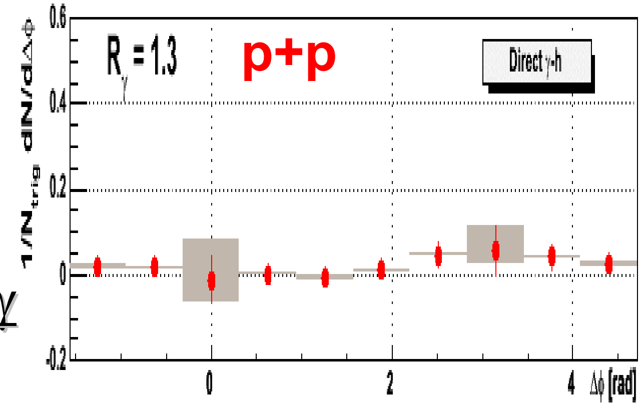
(Use pair by pair waiting with MC factor for prob. That π^0 at given p_T decays to γ in p_T range of interest)



❸ *subtract decay γ-h per trigger yield from γ-h per trigger yield*

$$Y_{dir-h} = \frac{1}{R-1}\left(RY_{inc-h} - Y_{dec-h}\right)$$

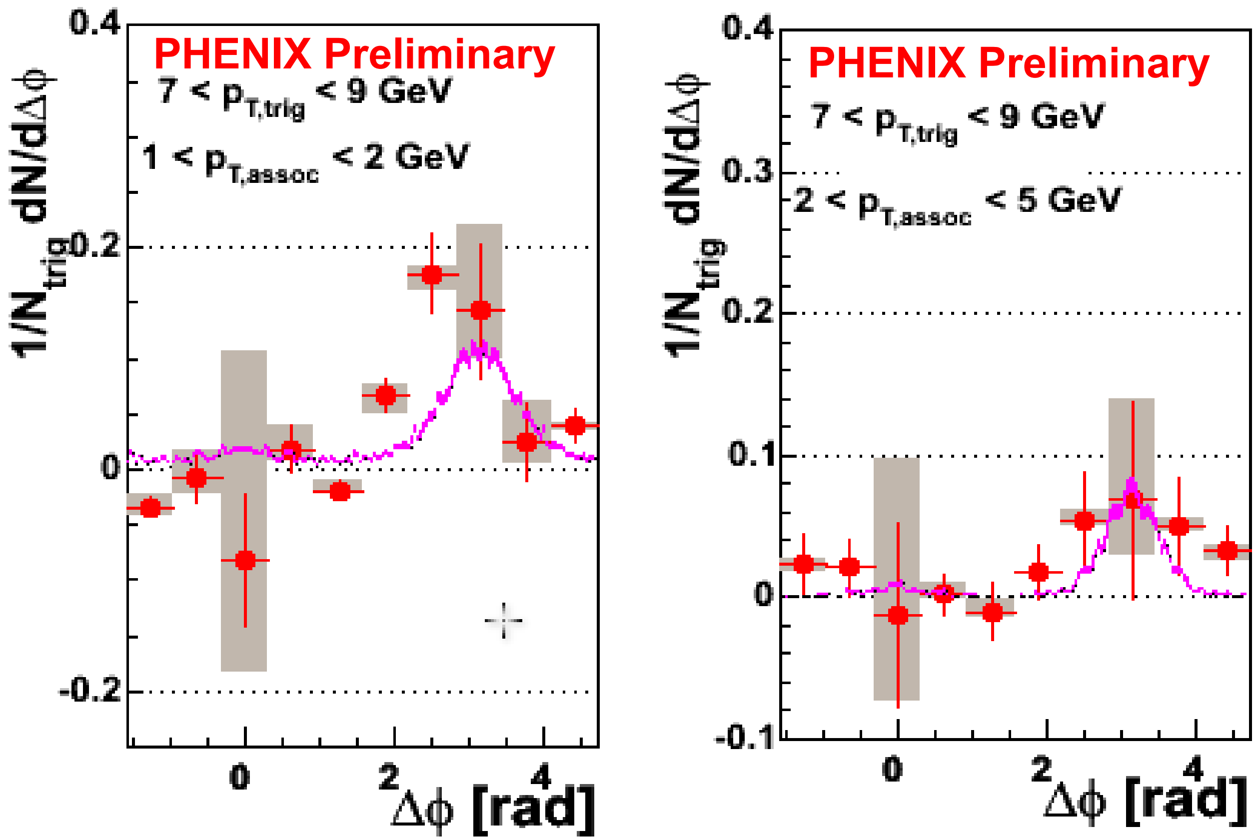
$$R = \frac{\#\ \text{inclusive}\ \gamma}{\#\ \text{decay}\ \gamma}$$



γ-h Correlations in p+p

- data
- PYTHIA

PYTHIA 6.1
k_T = 2.5 GeV

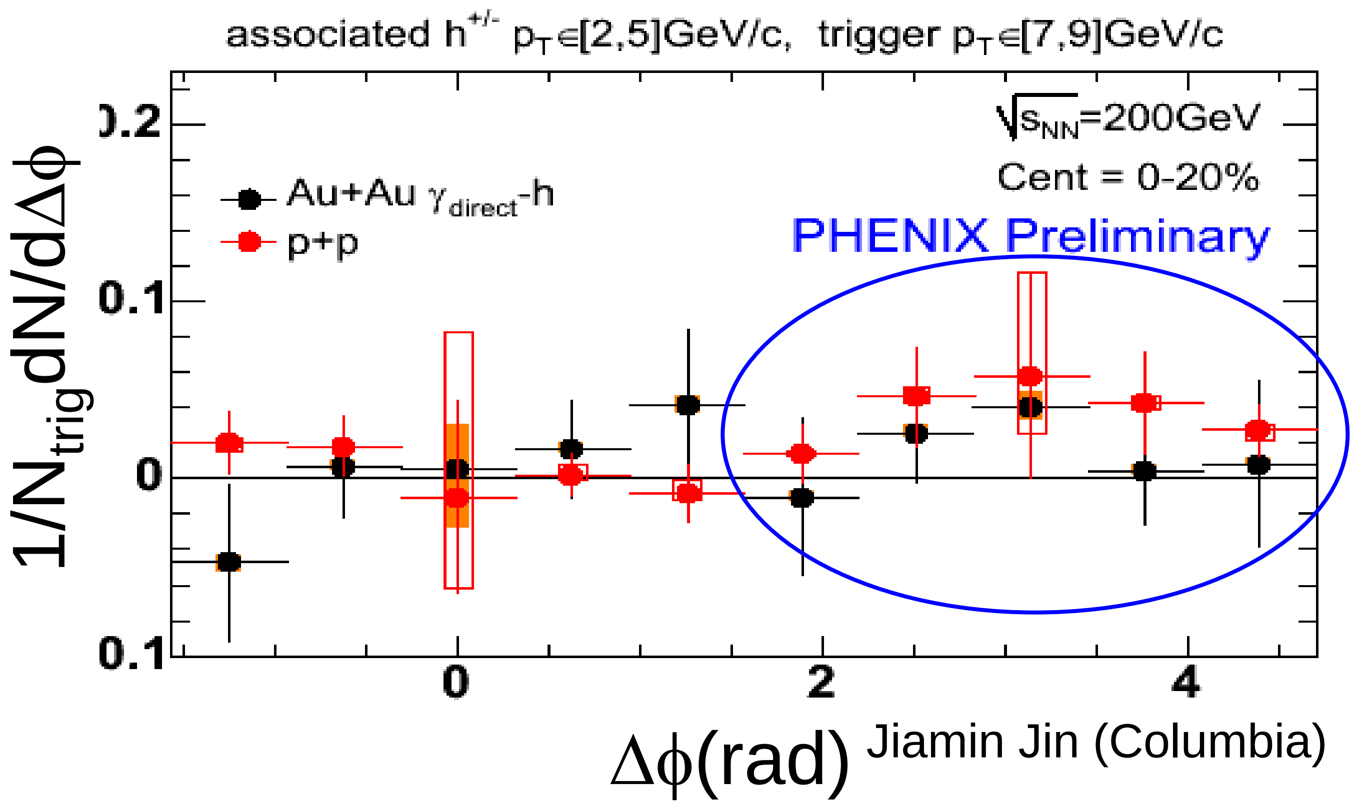


M. Nguyen (Stony Brook)

Reasonable agreement between data and PYTHIA

γ-h Correlations in Au+Au

Black: Au+Au   Red: p+p



Jiamin Jin (Columbia)

We have the tools,
we just need the statistics…